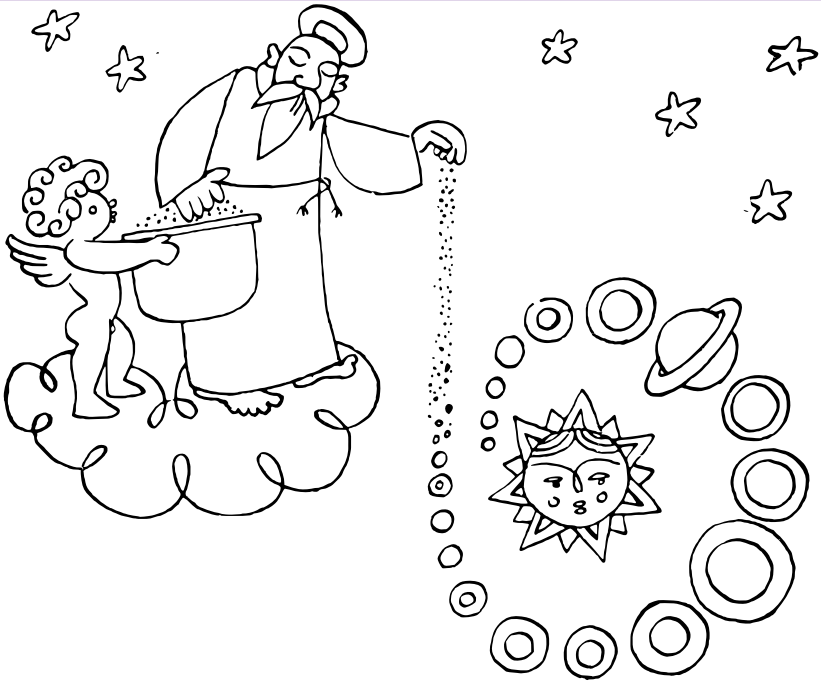
Eureka

Fascinating Cosmogony

Anatoli Tomilin



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Eureka

Fascinating Cosmogony

Anatoli Tomilin

A. Tomilin is an Institute lecturer and a member of the Writers' Union. **Fascinating Cosmogony** is not the author's first book. Young readers have frequently encountered his name on the pages of magazines and in scientific and artistic collections. Several works published by the **Detskaya Literatura** publishing house belong to him, including the book **The Earth's Sky**, as well as **Fascinating Astronomy** and **Fascinating Cosmology** Molodaya Gvardiya.

This new book by A. Tomilin, which the publishers offer to their readers, is also dedicated to one of the fundamental sciences of the universe.

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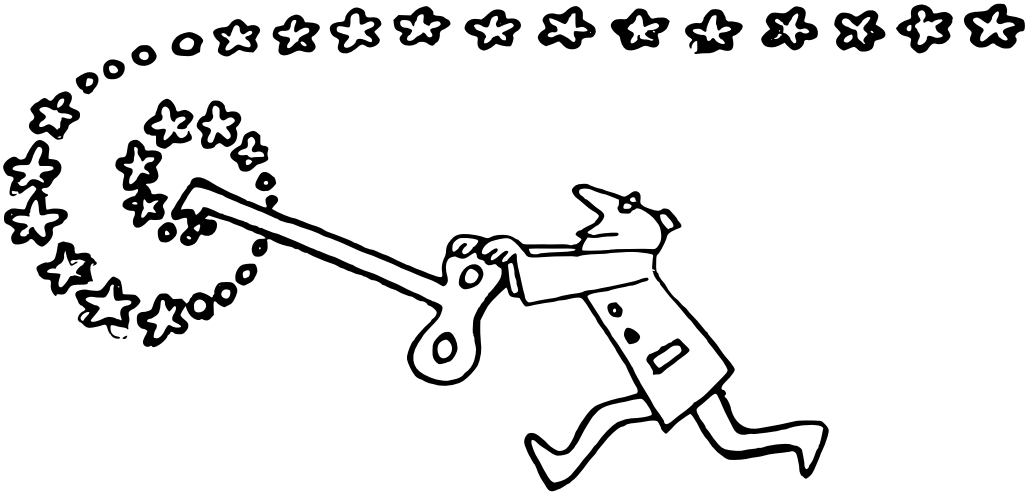

FASCINATING COSMOGONY

Anatoli Tomilin

Translated from the Russian by
Damitr Mazanav

The Mir Titles Project 2026

Anatoli Nikolaevich Tomilin
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Translated from the Russian & typeset in LaTeX by *Damitr Mazanav*

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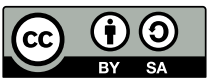

Annotation

A book of essays exploring the hypotheses devised by humankind to explain the origin of the planets, stars, and galaxies. It also looks at some of the creators of these theories—from ancient philosophers and priests through to modern astronomers, physicists, and mathematicians.

The mysteries of the universe powerfully draw humanity towards them. One of these is how the Solar System and the systems of other stars originated and developed. There have been many assumptions on this matter, but all of them were speculative in nature. It is only in our time—the era of automatic interplanetary probe flights—that we have managed to measure some things directly on celestial bodies and put forward more reliable hypotheses. This book discusses the modern view on the genesis of our world and the processes of world formation.

Translator's Note

This is the third book I am translating the *Eureka* series. The author A.N. Tomilin has written several popular science books.

Since the book was written in 1975, several speculative hypotheses presented in the book have not been supported by data. To indicate this, at some places I have added sidenotes with my initials "DM". I have also added a Postface which summarises some of the major landmarks in the themes discussed since the book was written in 1975. Mistakes and omissions (and I am sure they will be there), if any, are my own.

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1 Introduction

> Many hypotheses concerning the heavens may be formed which differ greatly from one another, and yet are all sufficiently consistent with the phenomena.
>
> Francis Bacon

"**Cosmogony** — is the science of the origin and development of celestial bodies and their systems; a branch of astronomy" — that is the definition given in the encyclopaedia. **Astronomy**, in turn, is the most ancient branch of human knowledge. Its history is closely intertwined with the entire process of the development of human society.

In his *History of Astronomy*, the eminent Dutch scientist and public figure A. Pannekoek writes:

> "If the modern physicist looks back at his predecessors, those who first laid the foundations of the structure of science, he will find people like himself, with similar ideas about experiment and theory, about

> cause and effect (admittedly, these were the first, more complex investigations). If, however, the astronomer looks back at his predecessors, he will find Babylonian priests and seers, Greek philosophers, Muslim rulers, mediaeval monks, noblemen, and clergymen from the Renaissance, and so on, until he meets his colleagues in the form of scientists of the 17th and 18th centuries. For all of them, astronomy was not a limited branch of science, but a doctrine of the world closely connected with their thoughts and feelings, with their entire worldview."

The only thing that is difficult to agree with in that entire quotation is the use of the past tense. Astronomy (and perhaps, almost first and foremost, the section that interests us — cosmogony) was not just a doctrine of the world, but is a doctrine of the world, closely connected with people's thoughts and feelings, with their entire worldview, as it always has been, and always will be, a reflection of social life.

Perhaps no other science can boast such a keen interest in its problems and discoveries. One need only recall the debates and arguments that periodically flare up in the press, whether concerning the Martian canals, the mysterious signals from space, the enigmatic "quasars", the hypothetical "black" and "white holes", or... fantastic films dedicated to "memories of the future". All these are links in one chain: attempts to define, clarify, and concretise one's system of views on the world, to determine the place within it occupied by individual phenomena — and above all, phenomena like the birth of planets, star systems, and

galaxies — and what relationship this tremendous spectacle bears to our own role in the world! Every person must ponder this at some point.

The cognitive significance of astronomy is primarily defined by the fact that it demonstrated that the Earth — is not the "centre of the universe", but merely an ordinary planet. As a result of this discovery, the entire religious worldview, in which man — the principal protagonist in the drama of salvation — was allotted a special, exceptional place, was shaken and subsequently destroyed.

This is why cosmogonical hypotheses — from the most ancient and primitive to the modern ones based on precise scientific data — have, in all ages, become the banner of an irreconcilable struggle between two opposing scientific movements: *materialism* and *idealism*. It is no wonder that almost all major scientists whose work paved the way for scientific cosmogonical hypotheses were subjected to persecution by the church and the powerful of this world. This struggle does not subside even in our day.

Cosmogony, being a branch of astronomy, is simultaneously inseparably linked to physics and mathematics. Without the application of their laws, formulae, and methods, it could not develop. In turn, cosmogony itself has had, and continues to have, a powerful influence on the development of related sciences. For instance, the development of cosmogony stimulated the study of nuclear processes occurring within the interiors of the Sun and other stars. The discovery of nuclear energy, in its turn, raised a num-

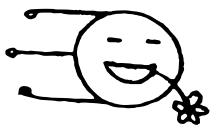
ber of questions directly relevant to cosmogony.

It is therefore fully justified that this book be devoted to essays concerning not only astronomy, but also physics and mathematics. Nevertheless, cosmogony remains the main focus here.

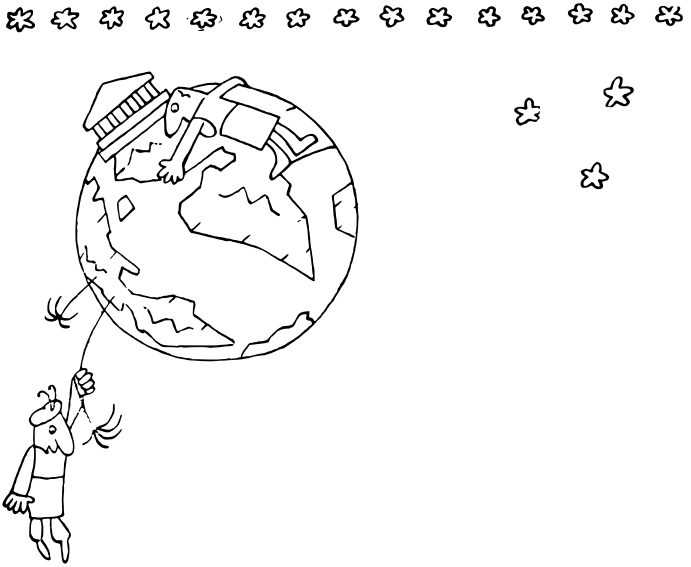
In the generalised system of human views of the world, which is usually called a "worldview", cosmogony occupies a significant place. Purely speculative in the past, today it is beginning to be based on facts, to operate with observational data, and to treat with a certain degree of distrust those theories which, while perhaps brilliant in form, are mathematically abstract and detached from astronomical practice.

Not so many years have passed, in the grand scheme of things, since G. Galilei pointed his telescope at the heavens and initiated the first revolution in astronomy. Yet today, astronomy is in the midst of a second revolution, and its most vital branch — cosmogony — is gathering facts and testing new tactics.

The objective of this book is to comment upon certain questions connected with the changing nature of our views on the problems of cosmogony.



2 When Gods Built The World



From Myths To Natural Philosophy

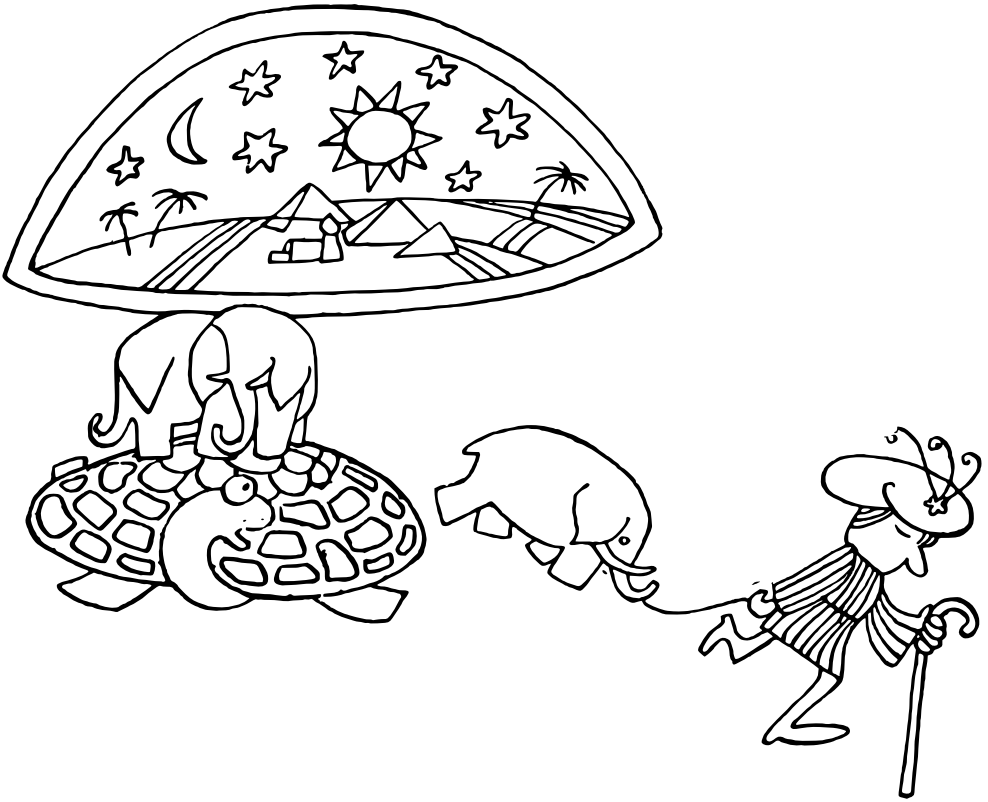
One of the most ancient models of the world known today apparently belongs to the Babylonians. This is followed by the Egyptian and Indian models... However, their roots go back so far into the depths of time that arguments about priority and attempts to place them in chronological order are simply inappropriate.

Despite their close connection with myths and the actions of the gods, ancient conceptions of the world were firmly based on common sense and reflected the settled way of life of the ancient people. The inhabitants of Babylon, who spent their days between the two great rivers, the Tigris and the Euphrates, imagined the Earth as a convex vault whose base rested upon the water. The land and the water were surrounded by the "Great Embankment of the Heavens", upon which the celestial dome rested.

The settlements of the ancient Egyptians lay in a narrow strip, extending from south to north amidst the impenetrable sands of the Libyan Desert. Further downriver, the mighty Nile widened the gorge into a valley with a wide, fertile delta. According to the firm conviction of the priests — the keepers of knowledge — the land of the God *Ra* (as Egypt was sometimes called) lay at the centre of the world; precisely at the spot where the Earth had sagged to prepare a fitting bed for the Nile.

Two thousand years ago, Indian scholars would tell their students about a milk-white sea in which a great

tortoise floats. On its back stand four elephants. Turning their heads towards the cardinal directions, they hold the Earth upon themselves. The world is enclosed by the coils of the black cobra *Shesha Naga*, whose thousand heads serve as the support for the universe.



How can this be? — The world is one, yet the Babylonian model differs from the Egyptian, the Egyptian from the Indian, and all of them from the Greek? Well, how would you imagine a whole when you have only a negligible part of it before your eyes? Presumably, by the image and likeness of the part?

People have always been interested in the origin and structure of the surrounding world. Besides purely pragmatic motives, a considerable role was also played by curiosity — one of the powerful aspects of reason. But to satisfy this need, knowledge is required. However, our ancestors could not boast of genuine knowledge regarding the causes of phenomena. So, to explain incomprehensible, immense, and terrifying natural phenomena, they were compelled to resort to the aid of supernatural forces — to invent **myths**.

Of course, the significance of myths is not limited to satisfying the purely cognitive needs of society. Mythology has deep social and historical roots and is a crucial, integral part of the entire spiritual culture. However, we shall deliberately limit ourselves to a chosen narrow aspect, one which relates only to the cosmogonical views of that era of religious-mythological cognition which precedes the scientific — or, more accurately, the initial natural philosophical — view of the world.

At the dawn of civilisation, myths filled the gaps in knowledge, closing the broken logical chain of understanding with links that were, admittedly, false, and made it pos-

sible to construct a temporary picture of the world. This was a very important task, because its resolution allowed humans to define their place in a hostile world and gain some measure of certainty. Biologists rightly believe that when a living organism encounters the unknown, a tension, as it were, arises in its system, preventing it from functioning normally. This tension can only be relieved by satisfying curiosity.

In the minds of our ancestors, the world differed little from the locality in which their native town or village was situated. And the gods built it using entirely human methods with readily available materials. Thus, while recounting the grand deeds of the gods, myths fundamentally provided pictures of the life of the very society in which the poets — the authors of the legends about gods and heroes — actually lived.

Throughout the history of civilisation, people have imposed their own order on nature, imagining the structure of the world from the standpoint of human expediency and dictating their own human laws to it. Anthropocentrism lives within us, despite the fact that our reason perfectly understands its complete untenability. Perhaps it will disappear entirely when the shining ships of aliens land on Earth's spaceports. Then again, perhaps it won't. Humanity might simply transfer the "centre of the world" from its own planet to another with a higher level of development. And then everything would start all over again. However, a joke of that nature does not sound terribly cheerful.

While the gods were building and perfecting the world, there was enough work for everyone. But later, through sheer idleness, they had to start concerning themselves with human affairs — tasks that were minor for celestial beings. Due to their enforced boredom, the gods frequently quarrelled, drank heavily on Olympus, and intervened in human disputes. Ultimately, their company began to take on a rather disorderly character. Meanwhile, every morning, without fail, the Sun rose directly after dawn. It gave people warmth and light regardless of the distractions that occupied Helios. Likewise, the custodian of the night, the Moon, accurately kept the calendar, entirely unconcerned with the feelings of Selene, who, according to myth, sighed for Endymion.

An insurmountable contradiction arose. On one side, a rather muddle-headed group of celestial beings decaying from idleness; on the other, the harmonious system of the universe with its eternal, unshakeable serenity. It is hardly surprising that doubts began to arise among some: "*Could this celestial crowd actually have created a world so harmonious and so expedient?*"

And here we find ourselves standing on the threshold of cosmogonies.

Still ahead are the digressions, the detours, and the zigzags of thought. Still will the flames of ignominious pyres rise to the clear sky and the smell of burning permeate the air. But the single seed of doubt, once sown, will give rise to such riotous growth that no holy herbicides can

suppress it: *the time of myths will inevitably be followed by the time of their rejection*.

We should not consider the ancient wise men to be stupider than ourselves just because they lived thousands of years ago and, not knowing the motorcar or trousers, preferred to walk and wrapped themselves in togas. From the very beginning, they perfectly understood all the advantages of the hypothesis of the divine origin of the world. Gods are omnipotent and gods are unknowable. And so, it is always proper to place their will and their deeds, like a full stop, at the end of any body of knowledge — neither explaining them nor, at the same time, permitting doubts. Faith stood behind the gods. And faith permits no doubts.

Thus, all myths were convenient primarily for the purpose of explanation, and they made their contribution to world culture. It must be noted that myths are convenient for explaining to others — to those who do not think for themselves, who need simple, ready-made truths, who are prepared to believe rather than suffer the torment of doubt. For the understanding of phenomena itself, science is needed. And before it could construct models of the universe, this science had to begin with the search for the prima materia: that substance which is capable of transforming into all things and into which everything must return after its end.

Perhaps before proceeding to an account of the first constructions by the ancient natural philosophers, it would be a good idea to summarise what they knew and what

interested them. It will then be easier to judge the facts that formed the basis of the first models of the world.

Our ancestors had more than enough reasons to be interested in the phenomena occurring in the sky. Life was rather monotonous, and the celestial phenomena served as their book, cinema, and television. Some of these were of a purely pragmatic in nature: measuring time, keeping a calendar and counting festivals, and navigation for seafarers and travellers. Others concerned the will of the gods, which was dictated by the stars, and the firm belief in the connection of every individual's fate with what was occurring overhead.

And today it is difficult to say which was, for instance, more important to the ancient Greeks. You might say: "*Astrology is a pseudoscience!*" But that is what you and I (two thousand years later!) know — that it is a pseudoscience. Our ancestors had no such suspicion!

Let us restrict ourselves in time to, say, the Alexandrian period of Greek scientific development — which is roughly the second century CE — and summarise the state of their astronomical knowledge.

From the Chaldeans[1], who were excellent observers, the ancient Greeks inherited a countless number of facts. Yet, even while compiling tables of planetary motion, the Babylonians evidently felt no need to explain them. Their priestly science was concerned with the registration of facts.

[1] The Chaldeans were originally a Semitic tribal group who settled in southern Mesopotamia. In later periods – especially in Greek usage – the term came to refer more broadly to Babylonian astronomer-priests, particularly those skilled in observation and astrology. The Babylonians, by contrast, refers to the wider civilisation centred on Babylon. That includes its political, cultural and scientific traditions across many centuries. – DM

The picture was different for the Greeks. Their science was democratic from the very beginning. Starting with Thales of Miletus and the Ionian school, Greek philosophers strove first and foremost to explain the phenomena. Among these were the rising and setting of the Sun and Moon, the capricious looping of the wandering lights of the planets among the "fixed" stars, as well as the ordered rotation of the entire stellar heaven. The minds of the first philosophers were also occupied by the causes of eclipses, the causes of lunar phases, and the nature of the heavenly bodies themselves.

Finally, the question of all questions, upon which the outcome of all other explanations depended, was — the shape of the Earth and its position in the universe. (We intentionally do not mention the "prime substance" from which the world was composed. This question is no less important than how the world is structured. Moreover, it was this very question that played the principal role in dividing natural philosophers into the irreconcilable camps of materialists and idealists. But it is better to recall the "prime substance" when discussing the corresponding cosmogonical models. That way, we shall stick closer to the topic.)

Thus, the first ancient Greek sages imagined the Earth in the form of a disc with protruding edges, either floating on water or suspended motionlessly in the air. Naturally, this disk was placed at the centre of the universe. The world was bounded by the sphere of "fixed" stars, which rotated uniformly around an invisible axis passing through

the poles. One pole was located in the region of the North Star; the other — somewhere in the south.

Explaining the movement of the Sun and Moon was more complicated, since, in circling the Earth, they lagged behind the stars. Furthermore, astronomers observed that the Sun rose higher at noon in the summer, and lower in the winter. Having separated the daily movement of the heavenly body from its yearly movement, ancient observers plotted its path onto star — celestial globes and called it the *ecliptic*, and the broad belt of constellations around the ecliptic was called the *Zodiac*. The Moon's monthly path and the complex routes of the planets traversed this belt.

When reasoning about the nature of celestial bodies, the ancient sages put forward the most diverse assumptions. Some regarded the Sun and Moon as merely flammable clouds that ignited at sunrise and went out at sunset, giving way to a new Sun and Moon the following day. There was also the opinion that the Moon was a vessel filled with fire. Its phases were visible depending on its position relative to the observer: in a full moon, the entire internal illuminated part could be seen through the mouth of the vessel, while at a new moon, the vessel — the Moon — turned its dark exterior shell towards the Earth. There were many different theories. But alongside ideas that appear clearly absurd to our enlightened eye, the philosopher Anaxagoras, as early as the 5th century BCE, offered a completely correct explanation for both the phases of the Moon and its eclipses.

Unsatisfactory too was the representation of the Earth as a flat pancake. Mariners knew for certain that upon approaching native shores, the coastal cliffs only gradually rose out of the sea depths. They also knew that in other lands, the stars in the alien sky were different. These facts demanded a new concept of the Earth.

And so, approximately in the 6 th century BCE, the Pythagorean school was formed in the Greek city-states, or poleis. Despite the wide fame of its founder's name, history knows virtually nothing reliable about the life and work of Pythagoras himself. Even the famous theorem, popular among schoolchildren of all times and peoples, was, according to the latest research, known to Egyptian land surveyors many years before Pythagoras's birth. Not a single line of this philosopher and mathematician's writings survived.

However, history has no doubts about the existence of Pythagoras's students, followers, and epigones. It turns out that the students took everything from the master except modesty, and the Pythagoreans left a great number of their own works. From these, we learned that they considered the Earth to be a sphere. One should not suspect them of exceptional insight, because in many respects this assertion was dictated not by scientific, but rather by ideological considerations. A sphere — a perfect figure, and the sphere was considered in the ancient world to be a divine and perfect figure because it is absolutely symmetrical. Now think for yourselves: could the gods, in creating the heart of the universe — the Earth — have made it imperfect? That

would be unbecoming of the gods!

Besides such important considerations, there were others, such as the round shadow of the Earth cast on the face of the Moon during an eclipse... In short, the Pythagoreans firmly maintained that the Earth was round and rested at the centre of the cosmos. The rest of the universe, in their opinion, consisted of transparent shell-like spheres that supported the celestial bodies.

The Greeks knew that the Sun, the Moon, and all the planets moved, lagging behind the rotating starry sky, and therefore distributed the heavenly bodies according to the speed of their movements. That was a successful guess, which allowed them to divide the planets into outer and inner ones relative to the Sun.

There were quite a few vulnerable points in the Pythagorean system. And true philosophers could not pass indifferently by one of them. The issue was: why did the daily movement of the Sun and planets occur from east to west, in accordance with the rotation of the sphere of fixed stars, while the annual movement of the Sun and planets occurred in the opposite direction?

Today, you and I understand this perfectly: the cause lies in the movement of the Earth itself. But the Pythagorean Earth was immobile.

Then a brave soul emerged — Philolaus, a student and follower of Pythagoras, who dared to shift the Earth from its established place and make it rotate. Philolaus taught:

"*The world is one and began to form from the centre*". He painted an amazing picture of the cosmos for his students.

In the centre, unlike his predecessors, the philosopher placed not the Earth, but a certain Central Fire — the hearth of the universe — which was tended by the goddess Hestia. Around it, ten divine bodies performed their circular dance: the sphere of fixed stars, five planets, the Sun, the Moon, the Earth, and the Counter-Earth (*Antichthon*). The latter was a special celestial body that helped explain solar eclipses, protected the antipodes from being scorched, and brought the total number of celestial objects up to the "perfect" number — ten. Note this example of the combination of ingenious foresight with the persistent superstition about numerical and geometrical perfection...

Philolaus's cautious followers abolished the Counter-Earth, returned the Earth to the centre of the universe, and placed the celestial fire inside the Earth. The only thing they allowed it to keep was its daily rotation.

These first constructions were of immense significance for the subsequent development of science. Of course, the Babylonian and Egyptian systems of rules and tables allowed for the prediction of celestial phenomena much more accurately than the naïve ancient Greek models. However, the latter provided a general conception of the structure of the universe, allowing people to perceive the rationality of its arrangement.

The next step was simply to find the best scheme that could satisfactorily explain all the peculiarities of the ob-

served phenomena. One of the first people to attempt this was the astronomer, mathematician, physician, and philosopher Eudoxus of Cnidus, who lived around the 4th century BCE. He devised a scheme consisting of a multitude of concentric spheres that enclosed the Earth like the leaves of a cabbage. He positioned the axes of rotation of these spheres in different directions so that the movements of several "shells" would collectively produce the observed movement of the celestial body.

> "To make a good theory, we must have simple principles or assumptions, and we must be able to deduce from them a scheme that will explain all the facts reasonably well."

— writes Professor Eric Rogers of Princeton University. This rule is equally applicable to both the speculative and the scientific method. And Eudoxus's system met these requirements. He employed 27 spheres, whose motion sufficiently well mimicked the observed movements of the planets. Later observations and refinements of these movements demanded the complication of Eudoxus's scheme. And this was accomplished simply by adding to the number of spheres. A magnificent principle! It could only be superseded by a simpler geometrical scheme built upon a different principle.

Towards the end of the 4th century BCE, Heraclides Ponticus, a philosopher of the Peripatetic school, proposed a slightly different model of the world. (Incidentally, the term Peripatetics referred to the followers of Aristotle, who liked to stroll through the Lyceum surrounded by his students

while delivering his lectures. The school's name comes from the Greek word περιπατεω (*peripateo*).— "I stroll".)

Observing how Mercury and Venus consistently remained close to the Sun, Heraclides declared that the Earth rotates on its axis, and that the Sun, although it still orbits the Earth, has its own satellites: Mercury and Venus. This was not yet a new principle, but the scheme lies right on the borderline of the hypothesis of Aristarchus of Samos — the unfulfilled ascent of heliocentrism.

Aristarchus of Samos lived in Alexandria. Historical information about him is also very scant. It is known only that he taught at the Musaeum during the reign of the first three Ptolemies, roughly from 310 to 230 BCE, and wrote many works. Only one of them has reached us:*On the Sizes and Distances of the Sun and Moon*.

Aristarchus was the first in the history of the ancient world to assert that the Sun is many times larger than the Earth. This supposition, combined with Heraclides' semi-heliocentric doctrine, seems to have played a role in the genesis of his new idea about the structure of the world. Aristarchus constructed the first heliocentric model!

What was the problem? Why didn't a revolution in astronomy happen, and why didn't the era of heliocentrism begin 1,800 years earlier than the ideas of N. Copernicus? Alas, the majority of the most prominent philosophers spoke out against Aristarchus's ideas. It is not enough to create a suitable hypothesis; one must be convinced that it corresponds to the facts. The calculations based on the

scheme of the Alexandrian philosopher, who retained circular planetary orbits, were far inferior in accuracy to the calculations based on the scheme of Eudoxus — which, though more complex, were closer to the observations. "*One must save the phenomena*"[2] — said Hipparchus — the greatest astronomer of the ancient world, returning to geocentrism and crystalline spheres. Aristarchus's contemporaries could also not forgive him for the humiliation they felt in abandoning the centre of the universe along with the Earth.

The Lord God, Ptolemy, and the Problem of the Algorithm

At the close of antiquity, in the 2nd century CE, the astronomer, mathematician, and astrologer Claudius Ptolemy collected the works of his predecessors, processed them, and, relying on the physics of the incomparable Aristotle, definitively set forth the geocentric system of the world with the Earth immovable at the centre.

Ptolemy abandoned the concentric spheres that moved the celestial bodies and constructed his model using a combination of deferents: eccentrics with epicycles superimposed upon them. We shall now explain what this means.

The fact is that even before the great Hipparchus, astronomers knew that the Sun and Moon did not perform their journeys uniformly. Yet, the principle of "perfect move-

[2] The expression "to save the phenomena" (from the Greek *sozein ta phainomena*) meant constructing a mathematical model that reproduces the observed motions of the heavenly bodies, without necessarily claiming that the model describes their true physical structure. In ancient astronomy, including that of *Hipparchus*, this approach justified retaining geometric devices such as epicycles and spheres so long as they accounted accurately for the visible planetary motions. – DM

ment" — which was deemed to be uniform motion in a circle — was still considered inviolable. Once again, facts came into contradiction with superstition, and people gave preference to the superstition.

> "The facts do not correspond to the theory? Well, so much the worse for the facts." How many more times this dogmatic motto would ring out in science.

And in the 1st century, and in the 10th, and in the 20th ... In different sciences...

Ancient Greek scientists resolved the contradiction that had arisen very ingeniously. As early as the 3rd century BCE, Apollonius of Perga introduced the concept of the eccentric to explain the non-uniform motion of the heavenly bodies — that is, a circumference along which the Sun moves uniformly, but whose centre does not coincide with the position of the Earth. To the terrestrial observer, the movement of the day-star will now appear non-uniform. But only appear so.

The same Apollonius proposed another explanation for the non-uniformity of movement using a combination of uniform motions in circles. Here, it was not the Sun itself that moved along the solar orbit around the Earth — the *deferent* — but the centre of a small circle — the *epicycle*. If the two movements were combined, the result was the Sun's movement along the eccentric.

His model was constructed on an *algorithm*. There was no room for the gods, and with the gods, faith disappeared

as well. This was no longer a conception of the world, but its mathematical scheme — the highest form of cognition, based on calculation. A model with which one could perform pre-calculations, and that is already science.

Unfortunately, the development of astronomy was halted at this point for 1,800 years. Antiquity was yielding its position, and the Middle Ages that replaced it, with its gloomy monasteries and the burning stakes of the Inquisition, chained the Earth to the centre of the universe with the fetters of religious dogma. A mere glance towards the heavens was met immediately with the retort: "Ptolemy. Axiom. Be silent!" There was no need for further development, improvement, or refinement of the Ptolemaic scheme. It fully satisfied all the demands placed upon it by the Church, and almost completely satisfied the demands of astronomical practice.

The new Christian ideology of society, which triumphed by the start of our era, was also satisfied with the Ptolemaic model at first. And following the free-thinking of the Greeks, the double dogma of geocentrism and the immobility of the Earth was passed down to the Christian world for many years. Closely linked to anthropocentrism, it was incorporated into the canons of religion.

Ptolemy's work was the crown jewel of the achievements of ancient astronomy. The centuries that followed were a period of the fall of science and a return to myths. But not to pagan myths with a pantheon of reckless gods, but to the ascetic myths of Christianity, which rejected

the joys of earthly life. If human life is merely a transitional stage to eternal afterlife existence, then why bother studying the motion of the stars? The astronomical and cosmogonical ideas of medieval Europeans are striking in their naïveté and even a kind of deliberate foolishness. It was as if no ancient philosophers had ever existed. Even Ptolemy seemed too revolutionary.

Beginning in the 7th century, a new powerful force transformed world culture. Arab countries rose and began to gain strength. Sciences, including astronomy, began to develop rapidly within them. True, no original models of the structure of the universe arose in the countries of the East. In most of them, Ptolemy's geometric constructions were developed. But it is difficult to say today what would have remained of humanity's intellectual conquests had Arab scholars, mathematicians, and astronomers not preserved them.

Meanwhile, even in Europe, engulfed by the gloom of ignorance, the fruits of truth were gradually beginning to swell with the sap of doubt once more. By first interpreting and then criticising the dogmas of religion through numerous heresies, European philosophers were learning.

By the time of the Renaissance, the writings of ancient authors were being drawn out of the dust of oblivion and studied with admiration, preparing the ground for the revolution of N. Copernicus. And so, in 1543, in a printing house in the city of Nuremberg, the final page of the thousandth copy of a book was pulled from the press. It had a

long Latin title, which translated meant: *Nicolaus Copernicus of Torun's Six Books Concerning the Revolutions of the Heavenly Spheres*.

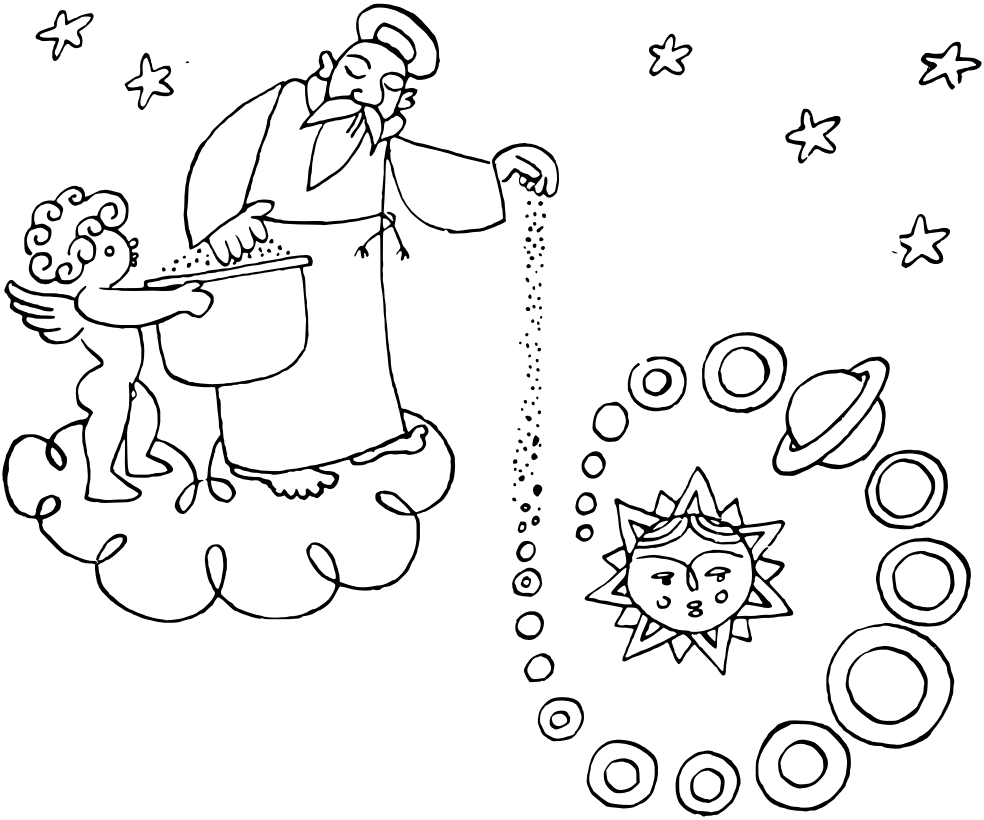
Copernicus's treatise postulated a system of the world consisting of the same concentric planetary spheres that the ancient Greeks had used. Only this time, the Sun, not the Earth, was at the centre. But was this really new? There had already been Pythagoras and Aristarchus... And in N. Copernicus's system, even the divine status of circular motions and the sphere of fixed stars remained unchanged. Having rejected the eccentrics and equants that had helped C. Ptolemy and his followers bring their calculations into line with observations, N. Copernicus was forced to retain the epicycles. Furthermore, the results of the pre-calculations based on the new model were no better than those derived from Ptolemy's good old rules.

More than half a century would have to pass before the "genius madman" J. Kepler transformed the orbital circles into ellipses and permanently freed humanity from those auxiliary geometric constructions.

N. Copernicus's contemporaries could not agree with much of his theory. They also could not understand how such a huge, massive body as the Earth could spin without causing a hurricane-force wind or deflecting the trajectory of a falling cannonball. G. Galilei (Galileo) was needed for science to eliminate these contradictions.

Another significant difficulty for the new theory was the absence of stellar parallax. "If the Earth moves around

the Sun," Copernicus's opponents argued, "then it should appear to the observer that the fixed stars also describe small circles. But this does not happen, does it?!"



N. Copernicus was greatly distressed that he could of-

fer no rebuttal to such reproaches. He comforted himself with the thought that the distance to the stellar sphere was so immense that the parallax was simply imperceptible. However, this consolation was weak, and his enemies gloated. Almost **three hundred years** would pass before the first stellar parallaxes were discovered by W. Struve and F. Bessel.[3]

[3] Stellar parallax is the tiny apparent shift in a star's position caused by the Earth's motion around the Sun, and its measurement provides direct evidence of the Earth's orbital motion. In 1838, Struve measured the parallax of Vega at the Dorpat Observatory (in present-day Tartu, Estonia), while Bessel determined the parallax of 61 Cygni at the Königsberg Observatory in Prussia, marking the first reliable determinations of stellar distances. – DM

And yet, despite the inaccuracy of its pre-calculations and the lack of undisputed, weighty proofs, the new system was revolutionary. And many understood this. Most importantly, it was in tune with the coming epoch. The time had arrived for a decisive shift from scholasticism, dogma, and mysticism to science. The fundamental criticism of Aristotelianism was behind the people. The quantity of accumulated cultural values was bound to lead to qualitative changes. And the heliocentric system of Copernicus was the first swallow signalling the dawn of spring in world science.

The Polish astronomer's main idea was that the apparent movements of the celestial bodies were *not true, but only seemed so to observers on the surface of the Earth*. They seem so because he himself (the observer) is carried away by the globe, which is rotating and flying around the Sun. Copernicus writes that he had repeatedly sought a better explanation for planetary motions from various authors until he found among the ancient philosophers the opinion concerning the movement of the Earth itself.

This he adopted as his guide, mathematically and astro-

nomically developing a new system capable of explaining the observed phenomena to the same degree as the time-tested Ptolemaic system. Judging by the specific text of the treatise, N. Copernicus's task was simple—to develop a new algorithm, nothing more. But both the author of the new theory himself and the majority of the enlightened public understood the enormous philosophical and, one might say, epistemological charge contained within that innocent algorithm.

Even in the form in which the new system first emerged from the printing press, and despite its vestiges, it already possessed a number of advantages over Ptolemy's. In one stroke, the Copernicus model solved the problem of the motion of the inner planets — Mercury and Venus — which was insurmountable for the old theory. Since both planets always appeared as morning or evening stars, meaning they were quite rigidly tied to the Sun, Ptolemy had to arbitrarily bind them to the day-star and force them to move together with it. This caused astonishment. *Why could the other planets freely wander across the sky wherever they pleased?*

The system of N. Copernicus simply eliminated this question. Since both planets lie inside the Earth's orbit, they must follow the Sun during its rise or set when observed from Earth.

N. Copernicus's book was written in a very difficult language. Consequently, despite its revolutionary content, it was received rather calmly by his contemporaries. Few

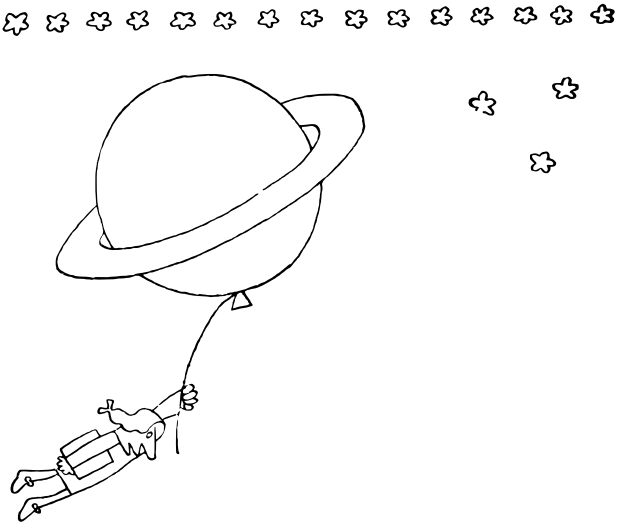
people read it. Even fewer understood it. It took a long time and many dramatic events before humanity accorded that treatise its proper place in history.

G. Bruno became a brilliant populariser and propagandist of the new doctrine, proclaiming the multiplicity of inhabited worlds. His hypothesis undermined the foundations of the dogmatic biblical cosmos. Meanwhile, J. Kepler's deduction of the elliptical shape for planetary orbits, along with his other two laws, definitively consigned to the dustbin of ideas the fundamental views of Pythagoras, Plato, and Aristotle, who held that only ideal circular motions were appropriate for ideal celestial bodies. And yet, N. Copernicus himself had adhered to those same views.

Kepler's laws not only eliminated one of the essential objections raised by opponents of the new theory — the non-uniformity of the planets' orbital speeds — but also shattered the crystalline spheres. The world became limitless.

Around the same time, G. Galilei (Galileo), by directing his telescope toward the heavens, initiated observational astronomy. He saw the moons of Jupiter, as if replicating the heliocentric system in miniature. But most importantly, he managed to express the process of motion mathematically, linking mechanics with mathematics and supporting the results of his calculations with investigative, and later demonstrative, experiments. Essentially, Galileo, building on the ideas of Copernicus, created the first example of the new science we call Physics today.

3 The Universe is Constructed by Philosophers



The Fulcrum

"Give me a place to stand, and I will move the Earth!" Who boasted that? You know, of course — Archimedes. He didn't move the world, but the thought was correct. In any revolutionary upheaval, a reliable basis is needed upon which one can confidently lean. Likewise, after criticising the biblical creation legend, philosophers needed to replace God with an equally reliable creative force.

The picture of the world constructed by the 17th century French philosopher René Descartes also grew out of the foundation of Copernicus's doctrine. God was in it, too. But not quite so omnipotent. Yes, God created matter, said the philosopher; God supplied it with motion, giving it the "first push." But thereafter, the solar system developed naturally, governed by the properties of matter and the motion of its disparate particles. Copernicus's theory states that all planets and all celestial bodies orbit the Sun? Excellent! Descartes makes a generalised premise-hypothesis: *the main form of motion for cosmic matter is the vortical movement of its simplest particles*. And immediately a beautiful and convincing picture of the formation of the world emerges.

Wait, what about God? Well, having created matter and pushed it, God had done his job, as the saying goes: "The Moor has done his duty, the Moor may go." In the swirling, circular motion, the particles, by coming into contact, interact, stick together, and form first clumps, which then turn into stars and planets. Note that the particles come into

contact; otherwise, how could they transmit their effect to one another? Descartes's picture was vivid and convincing. It's a pity only that no quantitative relations were derived within it. And the philosophy itself, despite the intention to put everything on a reliable mathematical foundation, was quite contradictory.

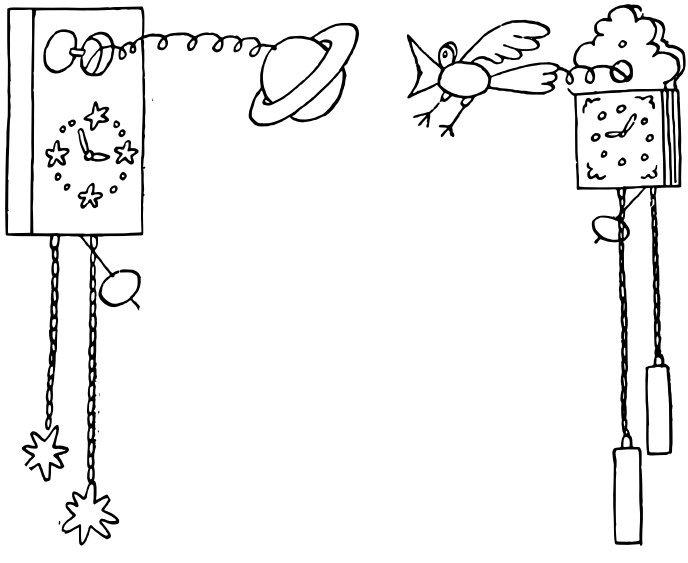
Only the method proved brilliant. Descartes counterposed his own method to the inductive method of natural investigation developed by the English scientist Francis Bacon. He was categorically against believing "the shaky testimony of the senses" and the "deceptive judgement of a disorderly imagination." No, no, only the deduction of consequences through strict mathematical and logical conclusions from general premises, leaving no doubt as to the power of the reason that generated them. In Descartes's opinion, only the deductive method was a reliable aid to the true philosopher-naturalist.

Following Descartes, the second major representative of mechanical materialism in 17th–18th century natural science must be Issac Newton, although Sir Isaac's cosmogonical views were not distinguished by particular originality.

Newton set forth the results of his work in mechanics in the treatise *Philosophiae Naturalis Principia Mathematica* (*The Mathematical Principles of Natural Philosophy*). This work, incidentally, was also written in a highly complex language. But in it, Newton demonstrated the immense theoretical and applied significance of the laws he had derived. The treatise contains solutions to a number of

crucial practical problems in mechanics and astronomy, but even more importantly, the *Principia* constituted a profound generalisation of all physics both past and contemporary to Newton.

Today, we are so accustomed to the classical formulation which states that "any two material particles attract each other with a force directly proportional to the product of their masses and inversely proportional to the square of the distance between them," that it even seems natural. Just as natural as the fact that the Earth is a sphere, and that this sphere rotates on its axis and orbits the Sun.



You believe in Newton's Law! Of course, one should believe in laws. Firstly, they carry the experience of generations within them. Secondly, they are usually so beautiful, so refined, that they are mesmerising. And finally, believing is much simpler than understanding...

Meanwhile, the habit of accepting any scientific assertion on faith leads to a certain degree of *dogmatism*. The situation with the Newtonian worldview was significantly more complex than, for example, with Descartes's picture of the world. Judge for yourselves: in Descartes's works, space was filled with subtle matter where vortices raged, transmitting force from one particle to another, and from the next to a third. That was as understandable as a nudge in the side. In Newton's works, space was empty, and the force of gravity acted at a distance. This caused bewilderment. After all, even the Lord God needed to send a lightning bolt to strike a person. In Newton's theory, people of the 17th century lacked a material carrier of the force. Furthermore, Sir Isaac's universe was eternal and unchanging.

Even from the perspective of our enlightened modernity, Descartes's idea about the development of the universe by means of internal forces of nature was much more progressive than Newtonian conservatism. And finally, the elegant language in which the French scientist's works were written was in no way comparable to the ponderous Latin of his English colleague.

All this led to a situation where, while bowing their

heads before the mathematical precision of the *Principia*, philosophers preferred the more vague French concept. Everyone agreed with reverence that Newton had taught people how to calculate the motions of celestial bodies. But Descartes offered the opportunity to reflect...

Of course, from today's perspective, one might suggest doing both simultaneously and together. But one should not forget that for a theory to capture the masses, it must first be made accessible to the masses. The principles of Newton were in need of popularisation.

Less than ten years after the death of the English physicist, his views "crossed the Channel." The work *Elements of Newton's Philosophy* was published, written in French, a language well-known to the European reader. The author of the book was F. Voltaire. His treatise played an enormous role in popularising the new ideas. And from roughly the middle of the 18th century, Newtonian principles and Newtonian mechanics began to dominate European science completely. They served as that "fulcrum" upon which one could lean to "move the world."

Thanks to the widespread dissemination of Newton's views, humanity was ripe for a new hypothesis. Now, its creator had to be found.

Georges-Louis Leclerc, Comte de Buffon, and the First True Cosmogony Hypothesis

The first hypothesis describing the creation of the Earth and planets based on Newton's laws and without the participation of God was the brainchild of a Frenchman. This was no accident. It was in 18th-century France, bubbling with hatred for the king and the nobles, in the atmosphere of an approaching revolution, that interest arose in a cosmogony rejecting the interference of higher powers.

And here before us is the first creator of a cosmogonical hypothesis, Georges-Louis Leclerc, Comte de Buffon. Tall, with an athletic build – wherever you look, a distinguished and presentable man. A small white wig under a three-cornered hat, a justaucorps[4] coat with wide cuffs. On his shoulders, a dark cloak covers a rather long rapier: the streets of Paris are not safe at night. Silk stockings and red-heeled shoes, such as dandies still wear, complete his attire. Buffon is 33 years old. He is not yet married. None of his numerous girlfriends has yet managed to completely captivate the athlete's heart. Alas, he is more attracted to the *Theory of Rockets and Methods for their Improvement*, which he is currently working on, and the nearly finished translation of the incomparable I. Newton's *Method of Fluxions*. However...

His full lips move. Stopping at the threshold of his house, he tells his servant that he is heading to the Medical Academy on Boulevard Saint-Germain. At this late hour?

[4] A justacorps or justaucorps is a knee-length coat worn by men in the latter half of the 17th century and throughout the 18th century. – DM

There he walks along the pavement of the street that would one day bear his name. His red heels stride firmly on the ground; his hat seems to brush against the stars. His thoughts are occupied by the movements of the planets. He is, as it were, turning the pages of Newton's *Principia* over and over again, reflecting on the "force of impulse," that is, the thrust that compelled the planets to move around the Sun. In Newton's view, this force is God.

But what does J. Buffon think? Let us take down a portion of his reflections: "... the force of impulse was, of course, imparted to the heavenly bodies by the hand of God when he set the universe in motion..." There is nothing new in these words yet. Descartes wrote this. Newton also wrote and said this.

But here is something new:

> "... but since physics must, as far as possible, refrain from appealing to causes lying outside of nature, it seems to me that this force of impulse in the solar system can be explained quite plausibly, and a cause found whose effect is consistent with the rules of mechanics, and which does not deviate from ideas relating to the changes and upheavals that can and must occur in the universe."

Well? A little old-fashioned in form, but how fresh in content. Do not forget that this is only the middle of the 18th-century.

In his thoughts, there is still a very cautious, but completely unambiguous desire to separate theology from me-

chanics, or "fable from physics," as he occasionally put it. He would later write about this in his work. And for now... He strolls unhurriedly through the streets of the old Latin Quarter — the quarter of scholars and students. And he reflects that every star in the heavens is a system, just like the Sun with its planets, all bound by the complex laws of mutual gravitation...

Georges-Louis strides past the church of the city's patron saint, Saint Genevieve. A few years later, by order of King Louis XV, the colossal building of the Panthéon would be laid on this very spot, where the ashes of many outstanding figures of French science would eventually rest. People are mortal; what can you do.

It was once believed that comets foretold the death of tyrants. At any rate, chronicles are full of descriptions of their appearance in the ruler's fateful year. Well, and if no comet appeared, but the king died anyway? The celestial body would be invented by the chronicler. Ridiculous people, those tyrants! They are often convinced, right up until their demise, that they are qualitatively different from other mortals. Buffon smiles. He recalls pages from the court chronicle, written just fifty years ago. In 1680, the Earth's sky was visited by a

> "new comet, such as had not been seen in recent times... Great fear reigns in the city: timid people see this heavenly body as a portent of a new flood, because, as they assert, a flood is always preceded by fire."

The Comet of 1680! According to the calculations of the

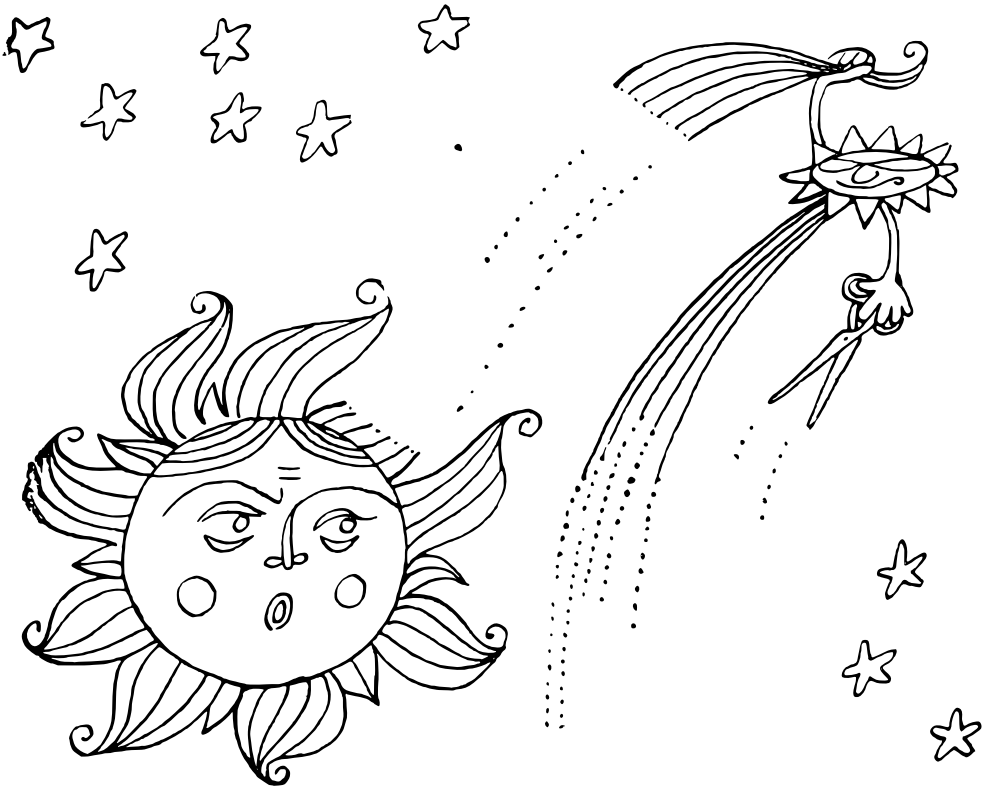
Englishman Edmund Halley, a friend of Newton, it passed so close to the Sun that it barely missed striking the great luminary. And it was a good thing it didn't. According to general consensus, comets are massive bodies wandering in space. Dangerous encounters with them have already been predicted for both the Sun and the Earth on more than one occasion.

The esteemed Masters of the Sorbonne gathered to discuss the danger posed by the wandering celestial body. That same famous Sorbonne, past which Buffon was now walking, and where, a few years later, his treatise would be condemned as heretical and contrary to Holy Scripture. But all that is still ahead. For now, Georges-Louis is unaware of it. He calmly crosses the Boulevard Saint-Michel as cheerful Parisian students call it to this day. His route takes him past the old church of Saint-Sulpice toward the Saint-Germain market...

It is already late. But torches are stuck in the ground near the oyster stalls, and vendors deftly pry open the shells with curved knives. Fresh goods have arrived. The smoke of braziers drifts through the air.

"Chestnuts, chestnuts, sweet roasted chestnuts." And there, by a long counter, is a high-wheeled cart laden with melons. Slap, slap – the golden-yellow fruits fly from palm to palm. The market gardeners are unloading their produce. The night is short. A new day will soon dawn, and Paris will demand food. A lot of food: many fruits, vegetables, meat, and bread. Good heavens, how much people

need!... One of the market gardeners stands on the cart, tossing melons. The other catches them and arranges them into a pyramid. The pile grows. What do they care about comets? They have probably not even heard of the ominous portents. But if this is God's wrath, is it fair that some of his children remain in ignorance?



Buffon recalls a dispute to which he was invited during his stay in London. One of the debaters — an astronomer — was frightening his opponent with the consequences of a comet's encounter with the Earth.

> "The formidable celestial body will strike the Earth from behind, slow down the planet's movement, and alter its path. The Earth will approach the Sun and ignite... Many years will pass before, reborn by fire, it is once again made habitable by God's will. And then the reign of the saints will begin upon it. After a thousand years, this reign will end, and the Earth will collide with one last comet. This time its orbit will be stretched, and, turning into a comet itself, the Earth will again become lifeless."

What a magnificent salad of astronomy, mysticism, and theology! However, P. Maupertuis — who is a friend of Buffon — also believed that if the Earth were to meet a comet, the impact would shift the poles to the equator. And Maupertuis, being both a physicist and an astronomer, certainly cannot be suspected of having a tendency toward mysticism.

But let us return to the thought of a comet meeting the Sun. Crash! One of the gardeners missed and did not catch a thrown melon. The round fruit struck loudly against the melon placed on top of the pyramid and split it open. Splashes of ripe juice and seeds made Buffon jump aside. The traders burst out laughing.

This small incident broke his train of thought. G. Buffon passed the market and walked along the Boulevard Saint-

Germain towards his chosen destination. Yes, so what was he thinking about? About the Sun and its meeting with a comet? That cursed melon! And yet, why should a comet not tear away a part of the great luminary's substance? And why should planets not form from this substance? A splendid idea! The episode with the melon gave it clarity and persuasiveness. A lively imagination filled the picture with details.

Time would pass, and he would describe how a huge comet flies towards the Sun, how on a "grazing" flight it barely touches the glowing surface of the star and knocks a part of its substance away. A giant tongue of solar matter stretches out to one side. Gradually, under the force of attraction in accordance with the law of Sir Isaac Newton, regions of density and thinness appear in the stream of matter. It breaks into parts. And from each part a planet begins to form.

Rotation gives them a spherical shape. As they slowly cool, the planets become covered with a glass-like crust. The same happens to the Earth. Inside it a core is formed. Vapours of the atmosphere condense and fall as heavy rains. A hot, boiling ocean covers the whole surface. Its waves wash away and break the fragile crust, grinding it into sand ... How well everything works out in this emotionally drawn "action"! Even the fact that all the planets move in the same direction found its explanation, as did the roughly equal tilt of their orbits.

When could this have happened? According to biblical

chronology, the world was created 5,508 years before the birth of Christ. No, Buffon could not agree with such a time span. The process of planet formation must take at least ... tens of thousands of years!

Ah, Georges-Louis Leclerc, Comte de Buffon! What are you raising your hand against, monsieur? The wasps' nest of the Catholic Church began to hum and buzz. We have caught him!

Who knows whether it was not the persecution by the servants of God that drew readers' attention and sympathy to his hypothesis? In a short time it gained very wide fame, although even during the author's lifetime astronomers began to have their first doubts. The cause of these doubts turned out to be the same Halley's Comet. In 1759 it appeared again in the skies of the Earth. But its motion, according to astronomers' calculations, had undergone many changes under the gravitational influence of Saturn and Jupiter. The planets themselves, however, remained on their prescribed orbits.

If this was so, then the mass of a comet could not be compared in any way with the mass of the Sun. This meant that other comets also could not be regarded as massive bodies capable, in a collision, of tearing away part of the Sun's matter. Might it then make sense to suppose some other path for the formation of the planetary system?

The Nebular Hypothesis of Immanuel Kant

In the preface to the very first edition of his *Principia*, I. Newton wrote that he saw the aim of physics as being "to recognise the forces of nature from the phenomena of motion, and then to explain the other phenomena by means of these forces". A fine programme of action! Perhaps, by studying the motions of celestial bodies, it would finally be possible to arrive at an explanation of the main question — the origin of the Earth, the solar system, and, in the end, the world itself.

In 1755, an anonymous work appeared in Königsberg entitled *Universal Natural History and Theory of the Heavens*, with the subtitle: "An Essay on the Structure and Mechanical Origin of the Entire Universe on the Basis of Newtonian Laws". This was already a clear step forward compared with the hypothesis of G. Buffon, which used only the idea of attraction. Moreover, in Buffon's view the cause that led to the formation of the solar system was dictated by chance — a catastrophe resulting from the collision of two celestial bodies. Had this not happened, the Earth might not have existed at all.

On dark autumn nights, the young philosopher — then still very young — would often gaze at the sky for a long time. In the misty band of the Milky Way he saw other planetary systems and other Suns. There was no doubt that the heavenly bodies belonging to a single system must be united by a common origin. The Earth and the Moon, Jupiter and all the other bodies were formed at the same

time as their central luminary.

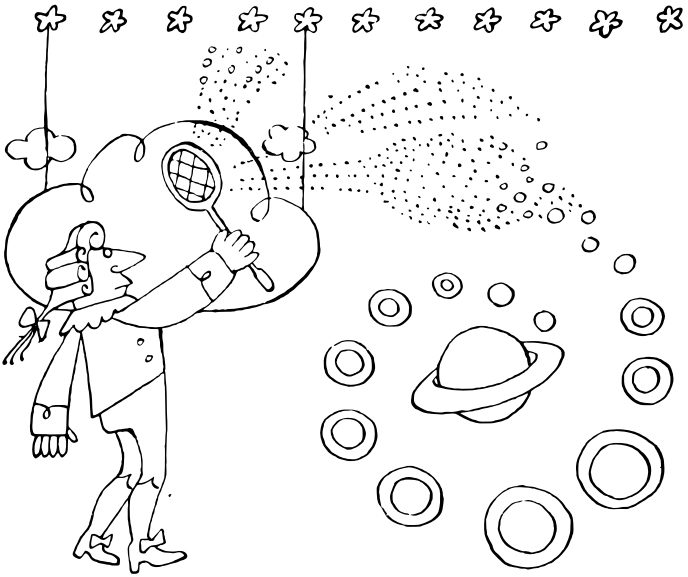
How else could one explain that, though separated by the empty vastness of space and connected by nothing except the force of mutual attraction, they have from the very beginning moved in the same direction in which the Sun itself turns on its axis.

But if the primordial cloud consisted of particles moving chaotically in different directions, how could they be made to start circling in one and the same direction? From the laws of I. Newton known to Kant, such an ordering of motions did not follow. And so philosophy came to the aid of mathematics. In addition to Newton's forces of attraction, he introduced forces of mutual repulsion. It was precisely these that were supposed to help the particles at first, and later the bodies formed from them, to acquire "free circular motion".

You may well ask: where did he dig up these forces from? Light pressure had not yet been discovered in Kant's time, and no one had yet thought of adapting forces of electrical repulsion for cosmogonic purposes either. What, then, was the nature of this repulsion?

Most likely, Kant's idea of these forces arose from the philosophy as old as the world itself — the dialectical idea of the interaction of opposites as a universal law of motion of the world. For even when he was engaged in natural science, Kant never ceased for a moment to be a philosopher. True, biographers write that for some time, while still a university student, he showed an inclination towards

the exact sciences. But they immediately add that this was largely just a reaction "to an excess of religious education at school".



At the age of twenty-two he even wrote an essay entitled *Thoughts on the True Estimation of Living Forces*, in which he analysed in detail the dispute between R. Descartes and G. Leibniz. The work of the philosophy student was written vividly and showed clear signs of independent thinking, but ... no more than that. And then, after finishing university and nine years of work as a tutor in private households — a role occupying an intermediate position between a

lackey and a poor dependent relative — he wrote a series of brilliant articles on cosmogonic problems.

Not only did he consider the questions that interested him from purely materialist positions, he also deprived God of the right to a "first impulse" and introduced the principle of the development of the cosmos. That very cosmos which, according to Holy Scripture, was created by God and has been unchanging from the beginning of time.

For the eighteenth century this was a bold conclusion. In his work *Anti-Dühring*, F. Engels gave a high assessment of Kant's cosmogony.

> "Kant's theory of the origin of all present heavenly bodies from rotating nebulous masses was the greatest achievement of astronomy since N. Copernicus. For the first time the idea was shaken that nature has no history in time ... It was, of course, obvious to everyone that nature is in constant motion, but this motion was imagined as the endless repetition of the same processes. In this view, which fully corresponded to the metaphysical mode of thinking, Kant made the first breach ..."

Unfortunately, Kant's contemporaries knew him only as a philosopher — the author of the critical method and the creator of a new critical philosophy. No one ever recalled his works in natural philosophy from the pre-critical period. Moreover, he himself later moved away from materialist positions. "The basic features of Kant's philosophy are a reconciliation of materialism and idealism, a compro-

mise between the two, a combination within one system of heterogeneous, opposing philosophical trends," wrote V.I. Lenin in his work *Materialism and Empirio-criticism*.

Years would pass. Critics would examine the German philosopher's hypothesis from physical and mathematical positions and prove, as clearly as two times two, that no internal forces are capable of setting the whole system of the nebula into rotation. Just as no one can carry himself across a river by pulling on his own hair.

So what, then, is the value of this hypothesis, unnoticed in its own time, and why, after so many years, have we not forgotten it, as we have forgotten many others that stand much closer to the truth of today?

One could, of course, say that Kant's hypothesis was the first in a broad class of cosmogonic hypotheses explaining the origin of celestial bodies from nebulae. Following Kant's, all of them received the general name "nebular", from the Latin word *nebula* — mist or cloud. But this is not the main point. No! Much more important is that Kant consciously viewed the development of the world as the result of opposing and contradictory forces of attraction and repulsion, and raised this method to a principle.

People had dimly guessed, even in the most ancient times, that the development of the world proceeds through the interaction of opposites, and they placed this idea at the foundations of dialectics. But only after Kant did the interaction of opposing principles begin to be systematically developed by later philosophers as a universal law of the

development of being and knowledge, until it finally found its full expression as the law of the unity and struggle of opposites in the works of K. Marx, F. Engels, and V. Lenin.

Today, the study of any object — from elementary particles and expanding galaxies to the biological and social laws that govern human beings and society — means, above all, penetrating into the contradictory nature of that object or phenomenon. And the deeper this penetration, the more accurate the theoretical understanding of the processes being studied.

Here we see the dualism of elementary particles, which reveal themselves as a unity of matter and field; the forces of gravitational attraction; the forces of electrical and magnetic repulsion. All this exists in the cosmos and all of it shapes galaxies.

Similar examples from any field of the study of inanimate and living nature can be found by the reader himself, if he takes the trouble to analyse the development of any system in the reality that surrounds him.

The Magnificent Five

In science one cannot make discoveries all the time. From time to time scientists must stop, look around, learn, accumulate knowledge, and only then rush forward again into the unknown.

When physicists, astronomers, and mathematicians

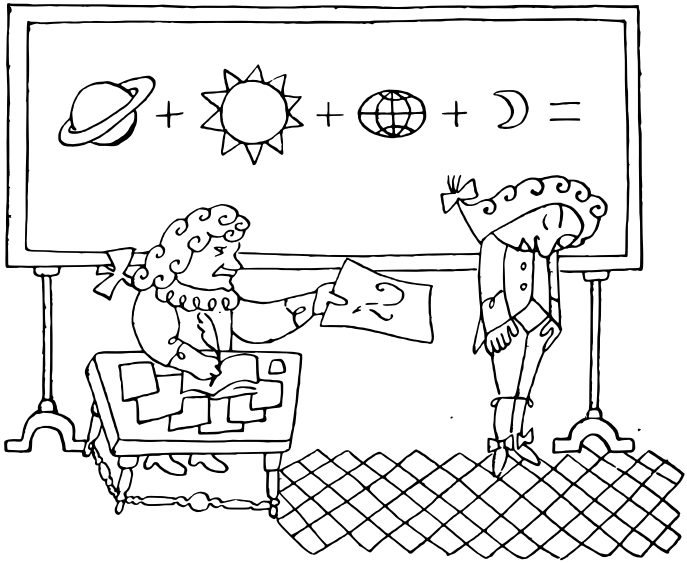
— and in the "good old days" all these roles were often combined in a single person — carefully studied Newton's incomparable Principia, they discovered much that was unexpected. In this astonishing book, for all its coherence and completeness, there turned out to be a mass of unfinished ideas and a multitude of problems: some were formulated and fully solved, others solved approximately, and still others were left only with an outlined path toward a solution. Here was ample space for successors to work.

For example, the law of universal gravitation allowed Newton to formulate and completely solve the "two-body problem", as the mathematical calculation of the motion of two mutually attracting material particles came to be called. This problem was especially important for astronomy, since it made it possible, for instance, to calculate the motion of the Moon in the Earth's gravitational field or the motion of any planet under the attraction of the Sun.

The solution of the "two-body problem" enabled I. Newton to confirm the validity of the first two laws of J. Kepler and to refine the third law. However, solving the equations of motion of an individual planet in the gravitational field of the Sun, without taking into account the gravitational forces of the other celestial bodies, proved to be valid only for short periods of time. From year to year, errors accumulated in such results due to the neglected small forces of mutual gravitation of the other members of the solar family.

The motions of the planets deviated from Keplerian

elliptical orbits, and the tables had to be revised and recalculated. No, the "two-body problem" turned out to be an overly approximate mathematical model.



At the beginning of the eighteenth century, astronomers counted eighteen legitimate members in the solar family. First of all, there was the Sun itself, then six planets: Mercury, Venus, Earth, Mars, Jupiter, and Saturn, as well as ten planetary satellites: the Moon, four satellites of Jupiter, and five satellites of Saturn. The last independent member of the solar system was considered to be the ring of Saturn, the nature of which was unknown to astronomers at

that time. All this company, bound together by the ties of gravitation that determined their mutual motions, had, in general, already been studied by humankind rather well.

For complete confidence in the boundless power of mathematics as a method of cognition, and of physical theory as the bible of this method, it remained only to solve the following problem:

> "**Given:** eighteen celestial bodies, whose positions and motions at a given moment are known.
> **Required:**to determine, by means of mathematics, from their mutual attractions, the positions and motions of each of them for any specified moment, and to show that the results of the calculations agree with observations."

That is all. Having solved this problem, humankind could have rested on its laurels, having rewritten the image of the god Sabaoth as the image of I. Newton. However, does the reader realise what it means to solve, with sufficient rigour, the problem of the motion of eighteen interconnected celestial bodies? Let us try to list only some of the difficulties that arise on the path to such a solution.

So, there are eighteen members of the solar system. Each of them, if regarded as absolutely rigid, that is, not subject to any deformations, possesses degrees of freedom. This is, of course, obvious, since they cannot only move in three different directions, but also rotate about three mutually perpendicular axes.

Consequently, in order to determine the position of a body in space, at each moment in time we must specify

numerical values for three coordinates and three angles of rotation. In total, six unknowns. However, the very process of motion is characterised by the rate of change in time of all these six quantities. Hence, there are six more unknowns. Multiplying twelve unknowns by the eighteen members of the solar family, we obtain a rather neat little system with 216 unknowns.

And now let the reader recall how difficulties progressed and marks in the school diary regressed when, at school, one moved from solving an equation with one unknown to solving a system of equations with two unknowns, then with three, and so on ... And in our case the troubles are far from ending with the number of unknowns alone. For an exact solution it would be desirable to take into account also the fact that none of the celestial bodies is absolutely rigid.

Changes in the shape of a body, tides and ebb tides alter both the speed of its rotation and the directions of its axes of rotation; the force of mutual attraction changes, and the orbits of satellites are disturbed. Moreover, there are also electrical and magnetic forces; the Sun loses mass every minute, which the planets acquire; the interplanetary medium has an influence, as does the combined gravitational action of the stars of the Galaxy; and, let the reader take this on trust, much, much else that affects the "position and motion of celestial bodies at any moment in time".

Even if we take into account that in the eighteenth cen-

tury half of the factors mentioned were unknown, the solution of the formulated problem presented insurmountable difficulties. It was necessary to find such a simplified version of it which, on the one hand, would be closer to the truth than the "two-body problem", and, on the other hand, would be practically solvable. In mathematics such problems are called "model problems".

In the Solar System, the principal force determining the motions of the planets is, of course, the attraction of the Sun. Of the planetary influences, it is probably sufficient to take into account only the influence of Jupiter, since it is the most massive. The remaining perturbations may be neglected in the case of a "model problem". Thus specialists arrived at the "three-body problem".

Unfortunately, its general solution also turned out to be so complex that until the beginning of the twentieth century there existed the view that obtaining such a solution was impossible. Almost all major mathematicians, astronomers, and mechanicians tested their abilities on this problem. And not without results. Very interesting solutions were obtained for particular simplified cases, which played an important role in the development of science. Especially much was done by five outstanding mathematicians who lived roughly in the same historical period.

First of all, this was a member of the St. Petersburg Academy of Sciences, L. Euler (1707–1783). He was followed by the French scholars — members of the Paris Academy:

A. Clairaut (1713–1765), J. Le Rond (1717–1783), who upon reaching adulthood adopted the surname d'Alembert, and J. Lagrange (1736–1813). All of them, with varying degrees of success, worked on solving the "three-body problem" as applied to lunar theory, considering the mutual influences of three celestial bodies: the Sun, the Earth, and the Moon.

The final member of the "Magnificent Five" of mathematicians was P. Laplace (1749–1827). With him begins a new period in cosmogony, and therefore we shall dwell in greater detail on the life and work of this most colourful figure of the turbulent era of the French Revolution.

Pierre-Simon Laplace and the Seventh Note to the Exposition of the System of the World

Pierre-Simon Laplace was born in the north of France into a peasant family. The boy's outstanding abilities prompted well-to-do neighbours to help him complete his schooling at a Benedictine monastery school. It is difficult to say what knowledge Laplace gained from this institution of the holy fathers. But that he became a convinced atheist precisely after finishing school leaves no room for doubt. At the age of seventeen he became a teacher at a higher school in his native town of Beaumont and wrote several mathematical papers. Then, armed with a letter of recommendation, he went to Paris to see Jean d'Alembert. However, the famous mathematician treated this provincial recommendation sceptically. Laplace then wrote, within a few days, a

work on the foundations of mechanics and sent it again to d'Alembert. Justice prevailed, and soon the young ambitious man was accepted onto the teaching staff of the Paris higher school.

Having barely established himself, Laplace began, one after another, to write and submit his works to the Paris Academy of Sciences. Rare perseverance combined with a definite mathematical talent led to the fact that at the age of twenty-four he became an adjunct, and at thirty-six a full member of the Academy.

Pierre-Simon Laplace, like no one else, knew how to single out what was essential in a problem under consideration; he knew how to present complex natural phenomena in mathematical form, to formulate the conditions of a problem, and to select an original method for its solution.

It is difficult to list Laplace's works — they are so numerous and so diverse. However, despite his fundamental research in mathematics and physics, the main part of his work relates to astronomy.

Laplace proved the stability of the structure of the solar system, that is, the constancy of the orbits and the invariability of the mean distances of the planets from the Sun. He discovered the causes of periodic inequalities in the motions of Jupiter and Saturn and, for this purpose, solved yet another particular case of the famous "three-body problem".

In studying the theory of the motion of Jupiter's satel-

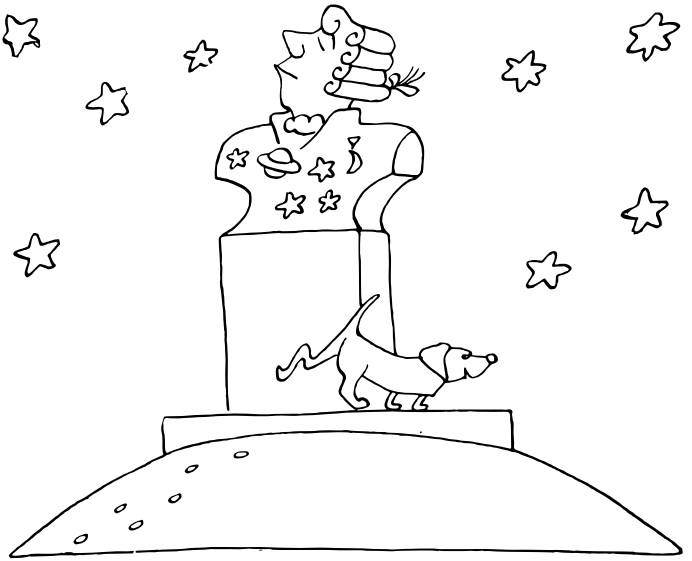
lites, he derived laws that bear his name and substantially supplemented lunar theory. It may be said that Laplace in fact completed it, providing a full theoretical calculation of the motion of the Moon — completed, of course, in the sense and at the level permitted by the state of science in his time. As the culmination of his astronomical work, one should mention the five-volume *Treatise on Celestial Mechanics*, in which, in a systematic exposition, he united the works of Isaac Newton, Leonhard Euler, Jean d'Alembert, and Alexis Clairaut, and in which Laplace himself gives a complete mathematical explanation of the motions of the bodies of the solar system.

In the preface to the first volume he writes,

> "At the end of the last century, Isaac Newton published his discovery of universal gravitation. Since that time, mathematicians have succeeded in reducing all known phenomena of the universe to this great law of nature and have thus achieved an unexpected degree of precision in astronomical theories and tables. My aim is to present, from a single point of view, theories scattered across different works, bringing together all results concerning the equilibrium and motion of solid and fluid bodies of which our solar system is composed, as well as similar systems spread throughout the vastness of the universe, and in this way to construct celestial mechanics.

This treatise became a classic during Laplace's lifetime. To this day, many ideas from this magnificent work lie at the foundation of theoretical astronomy, and its manner of exposition serves as a model for approaching theoret-

ical problems. It is said that his last words before death were: "How insignificant is what we know compared with the boundless realm of the unknown." Laplace was undoubtedly an outstanding scientist, a great scientist, a great mathematician.



How unfortunate that the assessment of his personality and human qualities cannot be expressed in the same terms. Laplace had a most unpleasant character. Extremely vain, arrogant, and rude towards people who stood below him on the social ladder, as well as towards colleagues, he could not tolerate the gentle Lagrange and quarrelled with Lavoisier. Perhaps the only person in the Academy towards

whom he behaved more or less decently was d'Alembert.

Laplace supported the republic, extolling freedom, equality, and fraternity. But when Napoleon became First Consul, the shrewd mathematician begged him for the post of domestic secretary. Dismissed after six weeks for his inability to perform this work, he was appointed, as a consolation, a member of the Senate. Laplace dedicated the third volume of his *Celestial Mechanics* to the "Heroic Pacifier of Europe", thereby obtaining from Emperor Napoleon the title of count. Yet only a few years later he voted for the deposition of his idol and joyfully welcomed the restoration of Louis XVIII. Ready to affirm and deny anything whatsoever for the sake of yet another order or ribbon, he later also received from the king the rank of marquis and the title of Peer of France.

Exposition of the System of the World is a popular work containing not a single formula and not a single diagram

The content of the *Exposition* is divided into five books. At the end there is a series of short notes. In the last – the seventh – a hypothesis on the origin of the Solar System is set out. Laplace himself says of this hypothesis that

> "these are conjectures about the formation of the stars and the Solar System – conjectures which I present with all the doubt that should be inspired in us by everything that is not the result of observation or calculation."

Laplace was always struck by certain features of the Solar System. First of all, why do all the planets known to observers revolve around the Sun in the same direction? And why do their orbits lie almost in a single plane? The satellites, too, for some reason move around their planets in the direct direction, and their orbits lie in closely similar planes.

The eccentricities of all planetary and satellite orbits are extremely small, and consequently their orbits are close to circles. At the same time, the orbits of comets are very elongated and, for some reason, can have any inclination with respect to the plane of the planetary orbits and the solar equator. In Laplace's view, it also required explanation why the Sun itself, and all the planets and satellites, rotate about their axes in the same direction. All these features seemed to push him towards the idea that a single cause, a single principle, must lie at the basis of creation...

And Laplace draws the conclusion: the various celestial bodies that form the Solar System and are governed by common rules of motion cannot have come together by chance. They must be united by a common origin.

Then, criticising the hypothesis of his compatriot J. Buffon (Laplace simply did not know of the existence of Kant's hypothesis), he says that the mechanism devised by Buffon is capable of explaining only the first feature of the Solar System — the common direction of planetary motion — and in no way explains the others. Moreover, the fact that the planetary orbits are almost circular indicates a low ini-

tial velocity of the solar material torn away by the comet. In that case, the condensate should have returned and fallen back again onto the surface of the luminary.

No, Laplace concludes, Buffon's hypothesis is incorrect. But how, then, can one imagine the mechanism of the formation of the Solar System? And here, before the reader, there unfolds in a strict logical sequence a new nebular hypothesis of the formation of celestial bodies from a primordial nebula rapidly rotating about its axis.

"What! Yet another nebular hypothesis?" Alas, yes. And not the last one, let us say frankly, looking ahead in time.

Laplace begins his hypothesis with the assumption that once, in the place of the entire Solar System, there existed a hot nebula rotating in the direct direction about an axis passing through its centre. Naturally, under the action of centrifugal forces, in accordance with the laws of mechanics, the nebula flattened into a huge disc, the edges of which extended far beyond the orbit of Uranus, the last planet known at that time.

Gradually the nebula cooled. And as it cooled, it contracted. But since its quantity of motion remained the same, as it contracted it rotated faster and faster. Thus figure skaters, wishing to speed up their rotation, tightly press their arms to their chest, and, conversely, as soon as they spread them out, the speed of rotation immediately decreases.

With the increase in the rate of rotation of the nebula, its regions farthest from the axis began to experience an ever-growing centrifugal force. And at a certain moment this force, for the most distant layer of the nebula, turned out to be greater than the force of attraction.

Then, from the flat nebulous cloud, a ring separated in the equatorial plane. With time, the central part turned out to be like a target, surrounded by an entire swarm of concentric rotating rings. Slowly — very slowly, from the standpoint of fleeting human life — the Sun formed from the central mass, while the rings broke up into separate condensations, which were attracted to and absorbed by the largest of them. Thus the planets and their satellites

were formed.

Sometimes, however, very rarely, Laplace believed, circumstances may arise in which the condensation of molecules of a gaseous ring occurs without its breaking up into separate parts. Then a continuous liquid or solid ring is formed from it, like the ring of Saturn, the nature of which was unknown at that time.

The harmonious line of reasoning was disturbed by comets, possessing elongated orbits with large eccentricities. Well then, what prevents one from assuming that they are visitors "from outside", captured by the Sun? Laplace thought exactly so. His hypothesis now explained all the features of the Solar System.

The situation was not, however, quite so satisfactory with the explanation of the direct direction of planetary rotation. According to Kepler's third law, within a ring the speed of particles should decrease with increasing distance from the centre. This meant that all the formed planets ought to rotate in the opposite direction, rather than in the direct one. This is especially easy to understand from a diagram which, unfortunately, Laplace did not provide. Apparently, however, he was aware of this flaw in the hypothesis and therefore hastened to assume that, owing to friction between particles, the inner boundary of the ring would lose a greater part of its speed than the outer one. As a result, the entire ring would rotate with the same angular velocity, as if it were solid. This would fully ensure the direct rotation of the future planets.

In its essence, Laplace's hypothesis is completely identical to that of Kant. For this reason, many years later it came to be called the Kant–Laplace hypothesis.

Great success fell to the book *Exposition of the System of the World*. The mathematician P. Laplace truly possessed a rare gift for popularisation. For himself, he played the same role that F. Voltaire had played for I. Newton. And, as often happens in history, the world remembered him not as the creator of the great *Celestial Mechanics*, but as the author of the *System of the World* and the originator of the nebular hypothesis. History seems to have its own criteria in such matters. They sometimes appear unjust to us.

Why, then, did the nebular point of view attract Laplace's attention in particular?

A contemporary of Laplace was William Herschel (1738-1822), the celebrated English observational astronomer. Herschel devoted much attention to nebulae. While compiling a catalogue of nebulous celestial objects, he produced many drawings. Looking at them, he noticed that all nebulae possessed central regions with varying degrees of condensation. These bright central nuclei Herschel regarded as stars in the process of formation. He wrote:

> "This point of view sheds new light on the structure of the heavens. They now appear to me as a magnificent garden, containing a great variety of plants, planted in different beds and found at different stages of development."

Laplace knew Herschel's works well and had no reason to

doubt the reliability of his observations. The conclusions of the English observational astronomer had a strong influence on the views of the French theoretical astronomer. Yet, since the materialist Laplace ultimately trusted only what could first be calculated and then verified by observation, he presented his hypothesis merely in the form of "conjectures and doubts". It was the task of his successors to provide it with a foundation of facts and calculations. And such successors did indeed appear.

In the middle of the nineteenth century, the French mathematician Édouard Roche showed that Laplace's nebula, as it cooled, must indeed rotate faster and faster. In doing so, it would inevitably flatten under the action of centrifugal force and acquire a lenticular shape. With further rotation, the separation and detachment of matter could begin from the edge of this "lens". However, if one imagines the ring torn away from the nebula as a continuous gaseous disc, its density would be so low that there would be no reason at all for the diffuse matter to gather into a denser formation — a planet. The force of attraction between the scattered particles would be far too small.

Édouard Roche was a fine mathematician and held Pierre-Simon Laplace in deep respect. In order to overcome the difficulty that had arisen, he assumed that the separation of matter occurred in the form of narrow, discrete "inner" rings. This idea was excellent not only because it removed the difficulty just mentioned, but also because it was the first to provide a more or less satisfactory explanation of the direct rotation of the planets.

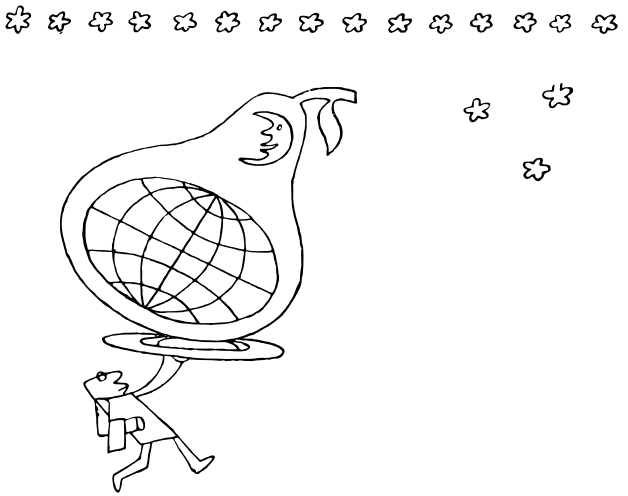
However, the memoir also contained a significant contradiction of Laplace. Roche asserted that Saturn's ring was not a remnant of the primordial nebula, confirming the correctness of the general idea, but rather the remains of a former satellite that had ventured too close to the planet and been "torn apart" by its gravitational forces. Roche even derived the minimum distance to which a fluid satellite can approach a planet without the danger of being torn apart by tidal forces.

As it approaches the planet, the satellite gradually begins to deform. In its equatorial region tidal "bulges" appear, aligned along the line connecting the centres of the satellite and the planet. After the satellite crosses the boundary of "safety" and enters the Roche zone, these tidal bulges turn into enormous tidal humps which, as a result of the satellite's rotation, run over its surface. Everything on it — mountains and valleys — is set in motion. And in the end the celestial body disintegrates.

Roche's work outlived the very hypothesis for which it was intended to serve merely as an auxiliary support, although in its own time it was unjustly forgotten.

For many years the hypothesis of P. Laplace enjoyed exceptional popularity. But the more popular an idea becomes, the more attention it attracts from its critics.

4 The Decline of the Nebular Hypothesis: The Beginning of the Assault



Do you remember that P. Laplace began his reasoning by listing the peculiar features of the Solar System? He then constructed a hypothesis that, as it seemed to him, explained all these features in the best possible way. But it was precisely with these features that the nebular hypothesis began to run into trouble.

Even during the lifetime of P. Laplace, W. Herschel discovered that two satellites of Uranus, which he himself had discovered, revolve around their planet in the reverse direction, and that the planes of their orbits are almost perpendicular to the plane of the planet's own orbit. This clearly contradicted Laplace's conditions. However, the creator of the nebular hypothesis, while preparing his book for new editions — it should be noted that during his lifetime it was reissued five times — did not consider it necessary to pay attention to this unpleasant news. Meanwhile, reverse motion was also found in other, newly discovered planetary satellites. Moreover, Uranus itself moved along its orbit, as observers put it, "lying on its side and slightly upside down". This meant that it too possessed *reverse rotation*. Similar suspicions were expressed by observers with regard to Neptune.

This was already a scandal. And then it was also discovered that Saturn's ring is not solid but composite, and that its inner parts rotate faster than the planet itself. Mars's satellite, the tiny Phobos, also overtook its planet. The mechanism of the formation of the Solar System proposed by P. Laplace could not withstand all this.

In the end, not only questions relating to celestial mechanics but also those of astrophysics were drawn into the orbit of fierce debates. In short, the nebular hypothesis had to be saved. Many heroic attempts were made to do so. Today it is almost impossible to arrange them all in chronological order, so closely intertwined they became. But it is worth dwelling on the main ones. They are far too interesting to ignore.

The cosmogonic hypothesis of Gervais-Auguste-Étienne-Alb(e) Faye

The French astronomer J. Faye, a member of the Paris Academy of Sciences, set out to strengthen the hypothesis of his compatriot P. Laplace. Above all, this required legitimising the retrograde motion of planets. However, he became carried away and, instead of making modest additions to Laplace's views, proposed his own large-scale version of the nebular hypothesis.

First of all, the French astronomer assumed the "pre-eternal existence of chaos" in the form of a cold and dark nebula. Laplace had not concerned himself with the question of where it came from. Faye, by contrast, decided to "ask God, as Descartes did, for dispersed matter and the forces governing it". These were his own words.

It is true that, having rather vaguely declared his adherence to divine intervention, he did not pursue this theme any further. After that, events unfold on their own. As

matter contracts, it heats up and eventually begins to glow, as is observed in nebulae. At the same time, he assumes that during the process of contraction the "chaos" is permeated by "streams of flying matter". When these streams meet, some of them form vortices — the progenitors of spiral nebulae, recently discovered by the English observer W. Parsons (Lord Rosse); other vortices give rise to stellar systems.

Fay considers double and multiple systems to be the main type of such formations. He insists that these are an exceptional rarity among stellar worlds. Only where

opposing streams of matter have passed by each other do clouds of "small incandescent bodies" gradually condense, forming planetary systems.

Fay proposed a mechanism intended to explain the direct rotation of Mercury, Venus, Earth, Mars, Jupiter, and Saturn, while allowing retrograde rotation for Uranus and Neptune.

He argued that planet formation began with the gradual appearance of ring-like condensations, starting in the inner region of the nebula and moving outward. In a slowly rotating cloud behaving as a single whole, particle velocities increased with distance from the centre. As a result, the first six planets, formed within the dense primordial nebula, acquired normal prograde axial rotation. Around the same time, or slightly later, the future Sun condensed at the centre. This, he claimed, altered the governing force regime: central attraction, inversely proportional to the square of distance, now dominated. Particles no longer moved as parts of a single mass but followed Keplerian orbits, with velocities decreasing outward. Consequently, the outer planets, formed later, were expected to acquire retrograde rotation.

The internal consistency is clear; whether the physical assumptions are justified is another matter.

Thus, the Earth and five of its companions turned out to be older than the Sun, while Uranus and Neptune were younger. The French cosmologist was particularly pleased by the fact that, according to the biblical legend, the Earth

was also created before the Sun.

This example is especially revealing as a model of speculative thinking. Fay's hypothesis not only failed to free the nebular principle from the weaknesses of Laplace's theory, but added further conjectural assumptions and new difficulties of its own. The era of qualitative reasoning based on ad hoc logical constructions was drawing to a close. The time for mathematical models was approaching.

The Duel of George Howard Darwin and Alexander Mikhailovich Lyapunov

It is interesting to note that the Darwin dynasty turned service to science into a family tradition. The first of them, Erasmus Darwin (1731–1802), a well-known Scottish poet, was at the same time a rather capable natural scientist. The younger member of the clan, George Howard Darwin, the grandson and namesake of the world-famous bearded gentleman who travelled around the globe aboard the *Beagle* and gave humanity the theory of species, has to this day worthily represented English physics.

The work of George Howard Darwin (1845–1912) was devoted to questions concerning the evolution of the double planet "Earth-Moon". He set himself the task of clarifying the cosmogonic influence of tides generated by the Moon within the Earth and, correspondingly, those produced by the Earth within the Moon. These tidal waves, whose motion is directed opposite to the rotation of the Earth, slow

down our planet, gradually lengthening the length of the day. According to calculations, in about one hundred thousand years we lose one second. Such a deceleration seems negligible, yet it was precisely braking due to internal tides that was proposed as one of the means of saving Laplace's hypothesis. By means of the tidal mechanism, Darwin also attempted to explain changes in the direction of planetary rotation.

Initially, all the planets possessed retrograde rotation, he argued. However, planets that condensed from hot gaseous matter were at first in a liquid state. Under such conditions, tidal processes occurred within them many times more intensely than can be observed today. Tidal waves slowed these young celestial bodies so strongly that they eventually almost ceased rotating. Then, turning one side towards the Sun, they completed one rotation about their axis in a year. If by that time the planet had cooled and solidified, the character of its motion could be preserved for a long period. If, however, the process of cooling and contraction continued, then, according to the laws of mechanics, the rate of rotation had to increase continuously. That is, the planets would gradually begin to rotate in the direct sense.

From all that has been said, Darwin drew the following conclusion: the mechanism described forced the planets closest to the Sun to rotate in the direct direction, whereas those farther away, being subjected to tidal forces to a much lesser extent, preserved their original retrograde rotation.

Darwin's work was perhaps the most serious support for the nebular hypothesis. Many of his conclusions are valid, especially for the planets closest to the Sun — Mercury and Venus.

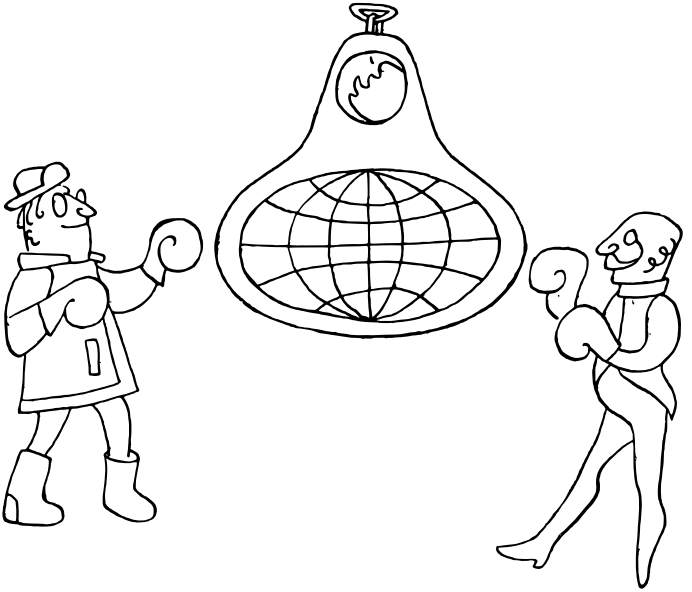
Considering the problem of the evolution of the Earth-Moon system, Darwin came to the conclusion that at one time a fairly large celestial body, heated to a liquid state, pear-shaped in form and moving in an orbit around the Earth, split into two parts. The larger part formed the Earth, the smaller the Moon. According to this theory, the division of a pear-shaped figure into two parts is possible only if the figure is stable. Otherwise, it should shatter completely. Darwin carried out a mathematical analysis which showed that a pear-shaped figure is stable.

But it is difficult to agree fully with this analysis, since the calculations were too approximate. A rigorous investigation of stability problems suitable for cosmogonic purposes proved to be extremely labour-intensive, and it was carried out only by our compatriot, the remarkable mathematician Alexander Mikhailovich Lyapunov (1857–1918).

Lyapunov was twenty-seven years old when he defended his master's dissertation at St Petersburg University on the topic "On the Stability of Ellipsoidal Forms of Equilibrium of a Rotating Fluid".

The work was devoted to the difficult problem of determining the stable forms of celestial bodies. At that time it was assumed that all solid celestial bodies had necessarily passed through a liquid phase, and the significance of the

Russian mathematician's memoir for cosmogony is hard to overestimate. Unfortunately, works written in Russian found their way to Western readers only with great difficulty. Lyapunov's dissertation likewise remained little known.



At approximately the same time, the question of what shape rotating homogeneous fluids in equilibrium assume was studied by the outstanding French mathematician Henri Poincaré. Independently of A. Lyapunov, he arrived at the same conclusion that was contained in the master's dissertation of his Russian colleague. Unlike Lyapunov's

memoir, Poincaré's work did not remain unknown. It made an enormous impression on the scientific world. G. Darwin was delighted. And no wonder: not only did Poincaré's theory confirm Darwin's hypothesis, and later his theory, it also allowed the English astronomer to advance yet another assumption about the formation of double stars.

According to this hypothesis, a homogeneous, liquid star rotating about its axis, as it cools, will contract and accordingly increase its rate of rotation, successively changing its shape. With further cooling, the rotating body must break apart, forming two stars.

This conclusion contradicted the results of A. Lyapunov. The Russian mathematician reconsidered the problem from the beginning and obtained convincing proof that the pear-shaped figure is unstable and therefore cannot divide into two bodies. Lyapunov published his results in French, and a long-lasting controversy arose between him and G. Darwin.

To convince the scientific world, Lyapunov single-handedly undertook an enormous programme of calculations, carefully documenting every step in a series of French memoirs. By 1914 this titanic work was completed, and the correctness of Lyapunov's conclusions was established. By then, however, neither Poincaré nor Darwin was still alive. The Laplacian hypothesis could not be saved.

Lyapunov devoted his entire life to science. Legends circulated about his capacity for work. To most colleagues

he appeared gloomy, severe, and extremely withdrawn, with almost no social circle. His brevity was absolute. Yet beneath this dry and pedantic exterior beat a loyal, very tender heart and a passionate temperament.

In 1918, alone in Odessa, holding his wife who was dying of tuberculosis, Lyapunov shot himself on the day of her death, leaving a request in his will to be buried together with her.

The Final Impulse and the Collapse of the Nebular Hypothesis

By 1900, so many contradictions had accumulated within Laplace's nebular hypothesis that it became obvious that the time for its replacement had come. However, for its final downfall an impulse was still required. There had to be a fact which, being absolutely clear to everyone, could find no explanation whatsoever within the framework of the existing hypothesis. Such a fact turned out to be the distribution of angular momentum in the Solar System.

What is meant by the "moment of momentum", also known as the "kinetic moment" or "angular momentum"? Above all, it is one of the most important dynamical characteristics of the motion of a material point or of an entire mechanical system. The concept of angular momentum is especially important in the study of rotational motion. For planets, it is the vector product of the mass of the celestial body, the velocity of its orbital motion, and its distance

from the Sun. This is the origin of the name itself: the product of mass and velocity is called momentum, and the vector product of a celestial body's momentum with the orbital radius is the moment of momentum.

If there is neither time nor inclination for calculations, one has to take it on trust. Let us take the angular momentum of the Earth as unity; then for the Sun it will be approximately twenty times greater. Let us write: Sun — 20, Earth — 1.

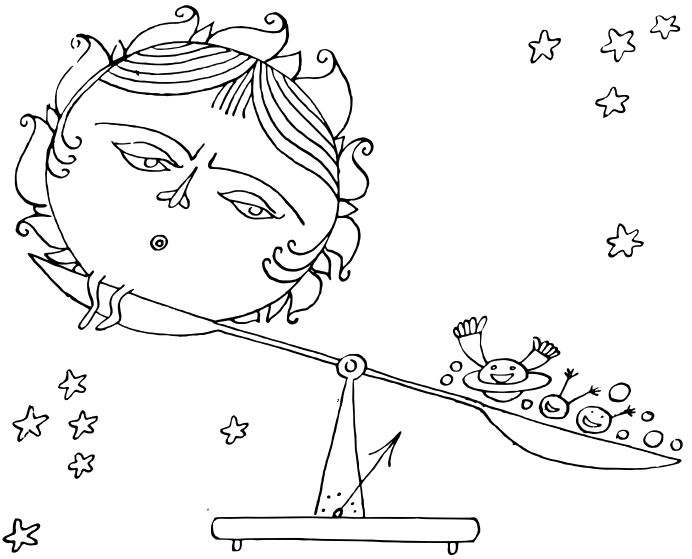
Further, the angular momenta of the remaining planets are distributed as follows:

Planet	Angular Momentum (Earth = 1)
Mercury	0.02
Venus	0.07
Mars	0.13
Jupiter	722.0
Saturn	293.0
Uranus	64.0
Neptune	94.0
Pluto	1.2

Altogether, if we add them up, we obtain 1174.42!

1174.42 for the planets versus 20.0 for the Sun? But how could it have happened that the massive central luminary turned out to possess less than 2 per cent of the total angular momentum, while more than 98 per cent fell to the share of the lightweight planets? The Kant–Laplace nebular hypothesis was unable to explain this fact in any way,

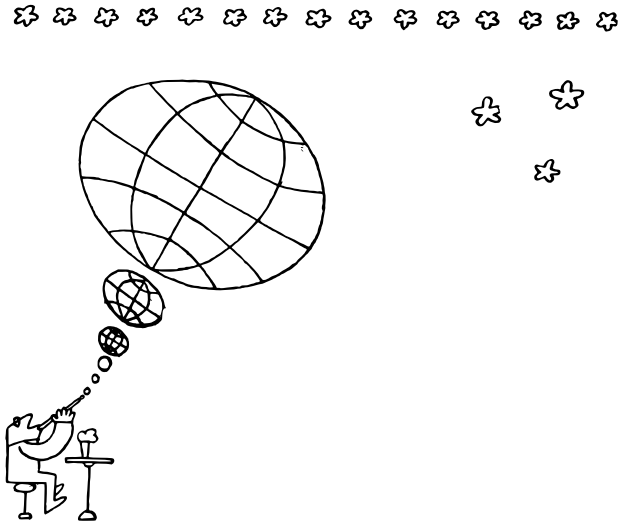
and it became its grave-digger.



This meant that one had to abandon the very idea of the gradual evolution of the Solar System and move to some other approach.

But to which one?

5 Planetary Cosmogony



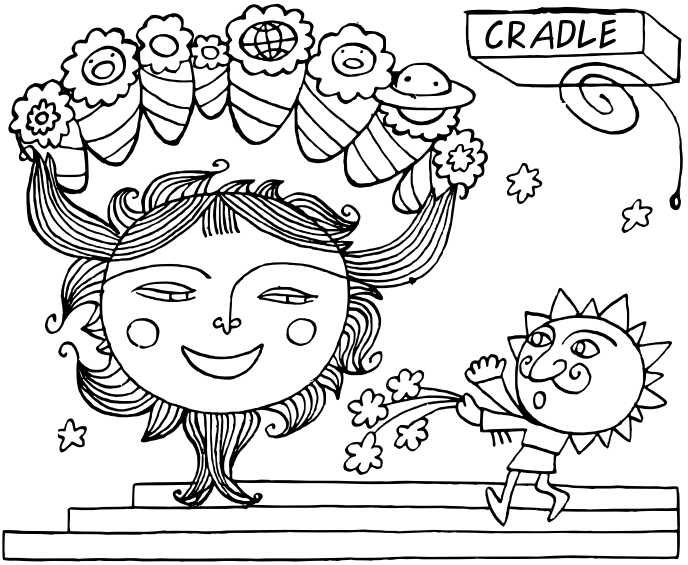
The Planetesimals of F. Moulton and T. Chamberlin

In 1905 the American astronomer Professor F. Moulton, together with his colleague, also a professor at the University of Chicago, though a geologist, T. Chamberlin, published a new hypothesis of the origin of the Solar System. They assumed that at some time our Sun, which did not yet have a planetary retinue, encountered another solitary star. The alien luminary passed so close to ours that a gigantic tidal wave of incandescent, compressed gases rose from the depths of the Sun. It rushed after the intruder. Subsequently, the large planets were formed from this matter.

From the opposite side of the Sun, where the tidal forces were much weaker, the eruptions were less intense. The masses of gas, retained by the Sun's gravitational field, were unable to escape far and formed the closely spaced small planets of the terrestrial group.

F. Moulton and T. Chamberlin envisaged the mechanism of planet formation from incandescent solar matter as follows. First, through condensation from clouds of gas, countless bodies of small size were formed; the authors of the new hypothesis called them *planetesimals*. The planetesimals rapidly cooled and solidified. Some of them, separating from the original assemblage, departed on independent paths along their own orbits. The rest, preserving their mutual connections, remained within large swarms which gradually, under the action of gravitational

forces, gathered into solid cores — the embryos of future planets. These cores revolved around the Sun within dense clouds of planetesimals along rather elongated orbits. This meant that their velocities were greater in some sections of the path and smaller in others. Passing through the boundless sea of planetesimals, the cores collected them and increased in size. Naturally, each captured fragment either slowed the core down if it was moving faster than the fragment, or, on the contrary, accelerated it if the core was moving more slowly. As the velocities were equalised, the shapes of the cores' orbits also changed, becoming less elongated.



The Moulton–Chamberlin hypothesis removed the difficulty in explaining the distribution of angular momentum. In addition, the star that arrived from outside somehow linked our Sun with the rest of the stellar world and included it in the history of the common life of the Galaxy. But it also had certain shortcomings. First of all, it was hard to understand what forces, apart from gravitation, could have assisted the ejection of masses of gas from the Sun. Perhaps light pressure, discovered by the Russian physicist P. Lebedev, could be adapted to this role?

In the opinion of most specialists, the forces of radiative repulsion are quite capable of competing with Newtonian gravitation. However, after calculations were carried out, the hopes revived by the subtle experiment of P. Lebedev were replaced by disappointment. The assumptions were correct, but only for bodies of microscopic size. Astronomers calculated that the entire enormous stream of solar radiation would barely be sufficient to counteract gravitational forces acting on a mass equal to that of an asteroid with a diameter of scarcely 15 kilometres.

It was also inexplicable in the assumption of F. Moulton and T. Chamberlin that the gaseous masses were ejected from the Sun not as a single continuous stream, but in separate clumps, as if as the result of a series of explosions. There were other critical remarks directed at the hypothesis of the American professors as well.

Some began to realise that it would most likely be impossible to explain such a grand and complex phenomenon

as the formation of the solar system by means of gravitational forces alone. It was then that the Scandinavian physicist K. Birkeland turned to the study of the "possibility of the outflow of charged particles from the Sun and the formation from them of rings whose radii depend on the ratio of the electric charge of the particles to their mass".

The conclusions of K. Birkeland did not prove convincing. The gap between the theories of electromagnetic and gravitational fields was still too great to allow any immediate hope of success from such a new approach to the problem.

James Jeans's "Cigar"

In 1917, a work by the young astronomer J. Jeans was published in England, entitled *The Motion of Masses under the Action of Tidal Forces, with Further Applications to Cosmogonic Theories*.

Two years later, his fundamental treatise *Problems of Cosmogony and Stellar Dynamics* appeared. In this work, J. Jeans summarised the entire body of experience achieved by celestial mechanics. And just as P. Laplace once began his treatise with a critique of Buffon's hypothesis, so J. Jeans begins with a critique of P. Laplace.

The reader may protest: "Why again P. Laplace? Why not F. Moulton and T. Chamberlin? Must we really begin from Adam every time?" The reason is that J. Jeans did not take the Americans' planetesimal hypothesis very seriously.

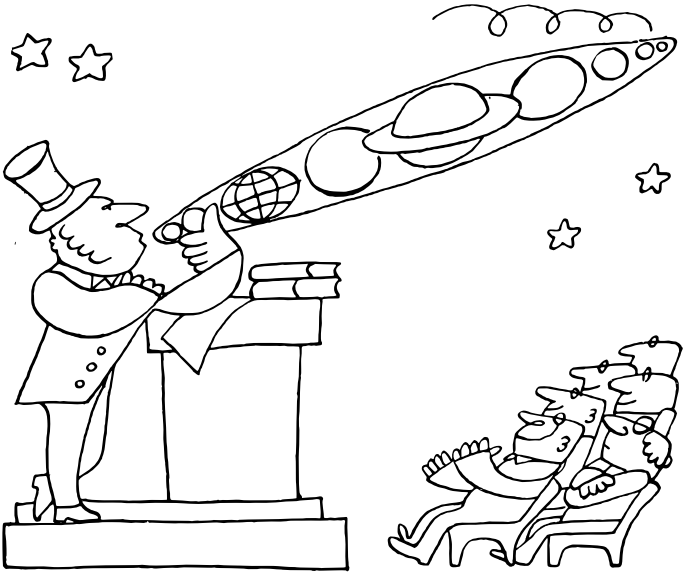
It did not provide an explanation for the origin of satellites. It did not explain why the orbits of most satellites are only slightly inclined relative to the orbits of the planets themselves. Moreover, being a specialist in gas dynamics, J. Jeans was firmly convinced that the ejected gaseous masses could under no circumstances condense on their own into dense planetesimals. They could, however, disperse into space, because a cloud of gas of planetesimal size has too little mass for the forces of mutual gravitation to overcome ordinary gas pressure. This was an important conclusion. It will be needed later, and therefore it is worth remembering.

J. Jeans focused on Laplace's theory as an example of what he regarded as a fundamentally impossible mechanism of planet formation. And if a planetary system cannot form gradually from a nebula, then only a catastrophe remains. *Tertium non datur*, as the ancient Romans used to say — "There is no third option!" And so the reader learns from Jeans's book about a meeting of the Sun with an unknown star, similar to that already proposed by F. Moulton and T. Chamberlin.

Turning to the description of his hypothesis of planetary system formation, the English astronomer states from the outset that this event is a pure accident, almost a miracle. By a rough estimate, the probability of such an encounter is no greater than one case in a trillion stars — a condition bordering on the practically impossible. That is, in our Galaxy, which contains only about one hundred billion stars, there is no reason even to expect a second such

encounter. These circumstances, however, did not trouble J. Jeans in the least. He later remarked,

> "Stars very rarely approach one another, and it is an almost incredibly rare event for two stars to come so close that planets are born. Planets, and it may be supposed life as well, are extremely rare in the universe. We may regard this with satisfaction or not, as we choose."



According to J. Jeans, the Sun was at first an ordinary solitary star that passed quite normally through all stages of its development. Then, several billion years ago, its path

was crossed by another star, probably a more massive one. If our Sun had been homogeneous throughout its depth, it would have been stretched out, turning into an ellipsoid. But since its density increases with depth, large tidal bulges formed on its surface, which developed into conical protrusions. When the distance between the Sun and the passing star approached the Roche limit, a violent eruption of solar material began from the apex of the tidal cone, like from a volcano.

The gigantic jet was supposed to resemble a cigar in shape, thickened in the middle, because the most intense eruption occurred at the moment when the star was closest. This "cigar" later broke up into separate condensations. From its thick central part the giant planets were formed, while from the thin ends the terrestrial planets arose.

J. Jeans had thought everything through and calculated it. The angular momentum was transferred to the planets by the passing star; it also imparted to them the direct direction of revolution. Their orbits were initially elongated and elliptical, but gradually, under the influence of braking in the remnants of the original gaseous matter, they became more circular. When the planets passed from the gaseous state to the liquid one, the same tidal forces formed a system of satellites around each of them.

Only comets and the small planets — *asteroids* — which by that time had already been discovered in considerable numbers, remained unexplained. For them, J. Jeans did not invent anything new. Comets, he believed, were captured

during their wanderings, while asteroids, mainly located in the region between the orbits of Mars and Jupiter, are fragments of some large planet. At some time in the past it came too close to Jupiter, and tidal forces tore its body apart. Plausible? Why not? Recall the work of É. Roche...

Everything seemed to be going very well. J. Jeans's hypothesis, in record time, captured the minds and hearts of his contemporaries. Specialists liked it for the rigour — one might even say the mathematical nature — of its reasoning; non-specialists were attracted by its vividness, as well as by the fact that it contained much that was familiar and customary alongside what was new and extraordinary. It is precisely such a combination, as is well known, that is especially appealing, stimulating curiosity.

The new hypothesis entered all textbooks. Neither theologians nor clerics uttered a word against it. Incidentally, why was that?

Because Jeans's assertion of the uniqueness of the formation of a planetary system, and of the even greater uniqueness — almost bordering on a miracle — of the origin of life upon it, poured water onto the worn wheel of religion. In short, the holy fathers, weary of applause, rubbed their hands with satisfaction.

There were, of course, weak points in this work as well. For example, the process of the formation of satellites, and also the explanation of the axial rotation of the planets. This is how J. Jeans attempted to solve the first problem. According to the hypothesis, the initial orbital motion of

the planets was very slow. And when the newly formed planets passed through perihelion for the first time, the Sun's gravitational forces tore away part of their substance, which then turned into their satellites.

However, most satellites are so small that, if at the initial moment they had consisted of gas, they would have dispersed immediately. After all, the force of attraction in small masses is far inferior to the internal gas pressure. The reader will recall that this followed directly from Jeans's own theory. This means that the satellites must initially have been either liquid or solid. The scientist was not troubled by the fact that it is impossible to tear off many small satellites from a liquid body. At best, tidal forces are capable of creating one large satellite, like our Moon. A solid body, under such circumstances, would simply crumble into pieces. No, something here was clearly amiss...

Matters were even worse with the explanation of the axial rotation of the planets. At one time, D. Darwin's tidal theory attributed the origin of planetary rotation mainly to the return fall onto their surfaces of part of the substance ejected during the formation of satellites. But in order, for example, to set Jupiter into rotation, the mass of the falling substance would have had to amount to approximately one fifteenth of the mass of the entire planet, which would be about four hundred times greater than the combined mass of all its satellites...

Thus, sceptical remarks about this splendid hypothesis gradually began to accumulate as well.

Additions by Harold Jeffreys and the Collapse of the "Catastrophic" Concept

In 1929, the English geophysicist Harold Jeffreys proposed a small addition to Jeans's hypothesis that removed the difficulty in explaining the axial rotation of the planets. Jeffreys suggested that the star did not pass the Sun at a large distance, merely reaching the Roche limit as in Jeans's model, but came much closer — perhaps even grazing our luminary. A "glancing lateral collision" occurred, after which the star, continuing its path along a hyperbolic orbit, disappeared into space. This catastrophe caused the ejection of a large quantity of matter from the Sun.

Jeffreys wrote,

> "Most of it, fell back onto the Sun; some portion may have followed the star or independently escaped into space; the remainder, deflected and set in motion by the star's attraction (or by the impulse of the collision, if it occurred), formed the raw material for the planets."

The turbulent — *vortical* — motion that arose in these remnants of diffuse matter then gave rise to the rotation of the future planets.

In 1935, at Princeton University (USA), the outstanding astronomer Henry Norris Russell was working. Even in those years he was called a figure of the first magnitude in astronomy. And then his popular science book appeared in print: *The Solar System And Its Origin*. Its purpose, as

he writes in the preface, "was only to set forth the present state of our knowledge of the solar system".

It is wonderful when a major scientist undertakes the popularisation of his science. Science at first hand — what could be better! But only when the aforementioned scientist does not merely expound trivial truths in a "simple language uncharacteristic of him", but gives his own assessment of the accumulated facts, acquaints the reader with his doubts, with his particular opinion. In short, when the scientist has something of his own to say on the chosen subject.

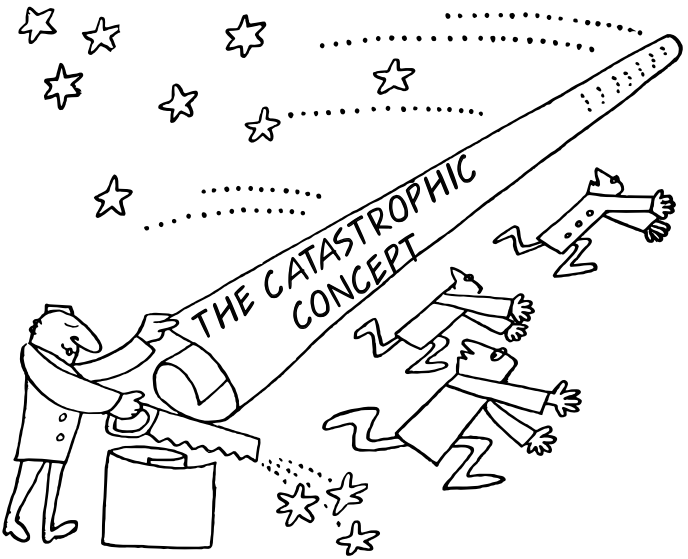
Russell was a real scientist, and therefore he did have "something to say"". Discussing Jeans's hypothesis, Russell lists a number of difficulties and dwells on one of them: "A much more serious difficulty arises when we consider the distribution of angular momentum — this time not the total momentum of the planets, but the momentum per ton..." And then, using the most elementary calculations, before the reader's eyes he obtains the specific angular momentum of the planets, on average about ten times greater than that of the star. And this is even under the most favourable conditions, from the point of view of Jeans's hypothesis.

Many difficulties were also caused by the explanation of the enormous size of the Solar System.

In short, after the intervention of H. Russell, the catastrophic hypothesis of Jeans–Jeffreys unexpectedly itself found itself facing a catastrophe. Both of its authors were concerned with the total angular momentum of the plan-

ets, and in this respect everything seemed to be in order. But it never even occurred to them to check how matters stood with the specific angular momenta. And this turned out to be fatal ...

H. Russell himself attempted to save their hypothesis by assuming "that before the encounter the Sun had been a double star and possessed a companion significantly smaller than itself, which revolved around it at a distance comparable to that of the major planets". A collision with a passing star (or perhaps a close approach) shattered this companion into fragments, which developed into the present planets.



H. Russell himself treated his own hypothesis with a sufficient degree of scepticism. He honestly pointed out a number of difficulties with which he was unable to cope. The first of them consisted in the fact that

> "...it is necessary either to assume that the Sun's companion had a small mass (less than one per cent of the Sun's mass), or to find a way to get rid of its remnant.
>
> I see no way to do the latter, except for the fantastic assumption that the passing star produced an almost central blow in the collision and carried everything away with it, except for a few splashes."

The difficulty was explained by the fact that stars so small, whose mass would be equal to the total mass of the planets of the Solar System, had never been observed by anyone. In our day it is considered proven that if a celestial body has a mass less than 0.07 of the solar mass, the necessary reactions simply do not arise in its interior that would be capable of turning a cold celestial body into a star.

The second difficulty, in Russell's opinion, consisted in the fact that

> "...we do not know whether a collision could split one mass into several parts of comparable size, and moreover the mathematical treatment of this problem would be extraordinarily difficult."

And

> "thirdly, it is improbable that the plane of the orbit of the Sun's original satellite and the plane of the orbit of the passing star were even roughly parallel. If this

> was not the case, then the separated fragments of the satellite would begin to move along orbits that were very strongly inclined relative to one another."

Nevertheless, the general idea expressed by H. Russell was taken up by the English astronomer R. Lyttleton. As a result of arduous calculations, he eventually proved that it is possible to find such initial conditions under which "a passing star, colliding or almost colliding with the Sun's original satellite, will eject it beyond the limits of the Sun's sphere of influence and itself will also fly off into infinity." In this case, a jet of gaseous matter could form between the passing star and the Sun's satellite. Part of it would have to be retained by the Sun, and planets would form from it.

This complication of the hypothesis led to an even smaller probability of an encounter between two stars than in the Jeans–Jeffreys case. In addition, if one calculates the energy balance, it turns out that ejecting the jet beyond the limits of the Sun's sphere of action would require about forty times less energy than tearing a jet of matter from it. Consequently, these two phenomena *cannot* exist simultaneously.

Between astronomers on all continents a fierce dispute broke out, during which every kind of accusation was used.

With the outbreak of the Second World War, the discussion lost its international character and subsided somewhat. True, in 1942 J. Jeans once again tried to return to his hypothesis, introducing a number of additions and clarifi-

cations. However, calculations published at the same time by the Soviet astronomer N. Pariiskii, together with new results on stellar evolution, reduced his efforts to nothing.

No, the catastrophic concept did not justify hopes either. H. Jeffreys publicly abandoned the hypothesis he had proposed, removing it from a new edition of his book *The Earth: Its Origin, History and Structure*. Moreover, opening the 1958 discussion at a symposium on the origin of the Earth and planets, he said: "I think I was asked to open the discussion because I am sceptical of all modern hypotheses."

This statement shows that, having abandoned the hypothesis of catastrophes after the nebular hypothesis, cosmologists had to direct their efforts towards the search for new possibilities.

In Search of New Paths

Already in the transitional years, when one cosmogonic concept was yielding its position to another, when new discoveries plunged the whole of physical science into a state of profound crisis, Russian, and later Soviet, scientists came to the fore in solving fundamental scientific problems.

At the end of the nineteenth century, the Kant–Laplace hypothesis was subjected to comprehensive criticism. However, the mechanism of the formation of the Earth itself remained almost untouched by criticism. It was still be-

lieved that, as a result of the contraction of pre-planetary bodies, their temperature increased and they melted. Then the glowing, incandescent bodies gradually cooled and became covered with a solid crust, while retaining fiery-liquid cores inside. This was how the planets of the Solar System were imagined.

The conviction that the Earth possesses a hot core was firmly based on numerous observations of the increase of temperature with depth in mines. By extrapolating the results obtained, geologists calculated the depths at which minerals should be in a molten state, and then pass into a gaseous state ... According to the Swedish physicist S. Arrhenius, who devoted much work to questions of cosmogony, the Earth's interior, heated to a gaseous state, is compressed so strongly that the gases are in fact solid bodies, which nevertheless can move easily with any change in pressure.

S. Arrhenius believed that the thickness of the Earth's crust does not exceed 40 kilometres, and that already at a depth of 300 kilometres the temperature is so high that all substances are in a gaseous state. The centre of the Earth, in his view, is filled with gaseous iron. The Swedish scientist considered that the radius of this core is no less than 80 per cent of the Earth's radius; 15 per cent is also occupied by a gaseous layer of magmatic rocks; 4 per cent by a fiery-liquid layer; and only 1 per cent of the Earth's radius, in his model, was occupied by the solid crust.

The conviction that the Earth was formed as a result of

slow cooling from a molten state was universal, and the replacement of the nebular hypothesis by the catastrophic one practically did not affect this view in any way: incandescent clumps of solar matter — future planets — also cooled, contracted, and became covered with a crust.

There were, admittedly, minor departures from the generally accepted opinion. Thus, the well-known Swedish polar explorer N. Nordenskiöld, a member of the Stockholm Academy and a corresponding member of the St Petersburg Academy of Sciences, having discovered "cosmic dust" in the depths of the icy deserts of Greenland, put forward his own cosmogonic hypothesis, which assumed the birth of the Earth as a result of the collision of meteorites. However, his point of view did not gain wide acceptance.

Suggestions were also made that the Earth's crust owed its origin to cosmic matter in the form of dust, stones, and other debris falling upon it. Geologists, however, were greatly troubled by the fact that the material of the planet's interior does not resemble matter that has undergone melting and reprocessing.

In 1896 the French physicist A. Becquerel discovered radioactivity — the ability of uranium compounds to emit invisible rays. In 1903 his compatriot P. Curie discovered that in radioactive elements, together with the decay of atoms, thermal radiation also occurs. Moreover, the latter clearly depends on time and on the number of decaying atoms. These works laid the foundation for a new view of

the geological history of the Earth and, consequently, of the cosmogony of the solar system.

In 1908, at a meeting of the British Association for the Advancement of Science in Dublin, Professor of Mineralogy and Crystallography at Dublin University D. Joly delivered a report on the geological significance of radioactivity. His conclusions were truly sensational. First, calculations showed that the amount of heat emitted by radioactive elements of the Earth's crust was quite sufficient to explain the existence of magma and volcanoes, as well as continental drift and mountain building. The speaker, however, did not dare to refute the opinion that the origin of heat inside the Earth was cosmic. But a seed of doubt had been sown.

After the report, one of the foreign guests approached D. Joly and said seriously and sincerely, thanking the speaker: "You have opened my eyes!"

This guest was the recently elected extraordinary member of the St. Petersburg Academy of Sciences and professor of Moscow University, Vladimir Ivanovich Vernadsky. His words were neither mere courtesy nor exaggeration. V. Vernadsky had come to Dublin with firm convictions of the Mendeleev school about the immutability of chemical elements and the indivisibility of atoms. And suddenly: "...the phenomena of radioactivity link matter with time in the sense that the element of matter — the atom — has a strictly defined duration, a finite existence, and inevitably decays in the course of time!" These words, with which

D. Joly ended his report, profoundly struck V. Vernadsky.

The congress was, beyond doubt, a success. One after another, chemists and physicists took the podium — scientists of world renown, with broad outlooks and profound knowledge. It was they who, through their experiments, shattered the established picture of the world, revealing new properties of matter. It was not easy for V. Vernadsky to find his way through the countless contradictions of the new physics, to grow accustomed to new concepts according to which familiar, seemingly dead and motionless matter consisted of atoms whose electrons were in constant motion. However, the powerful intellect and solid scientific training of V. Vernadsky enabled him not only to be astonished, but also to accept these new revolutionary ideas, which fundamentally changed the foundations of the existing worldview.

After returning home, V. Vernadsky increasingly reflected on the general scheme of the chemical history of the Earth. His imagination painted ever more grandiose pictures, in which our planet took its place on equal terms with other celestial bodies, united by common laws of the universe.

Only a year passed, and, opening the geological section of the Twelfth Congress of Russian Physicians and Naturalists, V. Vernadsky spoke of a new science — geochemistry. To study the history of atoms, understood as chemical elements on Earth, and from this to trace a path towards understanding the cosmos — these were the tasks

he set before the new science. The listeners watched, as if spellbound, the slender man standing at the lectern. His high, slightly muffled voice was not very expressive, and the report was long. Yet for three hours the tension did not leave those gathered in the hall, for what this sombre academician, with a deep gaze behind his spectacles and a rebellious forelock, was speaking about was new, original, and never heard before. Right there, in the hall, before their very eyes, Science was being created.

Over the years, V. Vernadsky firmly established himself as a supporter of the new atomic theory, astonishing his colleagues with unconventional conclusions and such broad generalisations that even they, accustomed to many surprises, could only shrug their shoulders.

Alongside his scientific work, V. Vernadsky devoted considerable effort to social and political activity. Intolerant of injustice, he resigned together with 124 professors and lecturers of Moscow University in protest against the repressions carried out by the tsarist government.

Accepting the Revolution, V. Vernadsky in 1918 took part in organising the Ukrainian Academy of Sciences. He had always loved Ukraine. His ancestors had lived on that land. Perhaps for this reason the young republican academy, whose first president was V. Vernadsky, so quickly became a powerful scientific institution.

In 1921, having returned to Petrograd, he and his pupil V. Khlopin organised the famous Radium Institute, from which later emerged a whole constellation of outstanding

Soviet physicists headed by I. Kurchatov. And throughout all these years he tirelessly promoted a new view of the geological history of the Earth. In *Essays on Geochemistry*, published in 1927, V. Vernadsky wrote:

> "...atomic radioactive heat, and not the residual heat of a cooling planet, as was thought until quite recently, is the principal source of that heat which explains all the geological processes taking place on Earth."

In 1937, at the Seventeenth International Geological Congress held in Moscow, V. Vernadsky finally formulated his view on the physico-chemical evolution of the Earth, incorporating it into the general cosmogony of the planetary system. In his report he stated with confidence that the Earth is a cold body, most probably formed in a likewise "cold manner". Even in the hottest centres of magma the temperature cannot rise above 1200 degrees.

Moreover, regions of high temperature are most likely concentrated in the Earth's crust; their thickness does not exceed 60 kilometres, and they do not constitute a continuous fiery-liquid layer. The temperature of the Earth's core, on the other hand, may turn out to be very low, not exceeding the temperature of meteorites reaching us from outer space. V. Vernadsky was convinced that the geological composition of the Earth *does not remain constant*. Slowly, atom by atom, some chemical elements perish, giving rise to others. In the scientist's view, all chemical elements are in a state of radioactive decay. People simply do not yet possess methods that would allow this phe-

nomenon to be detected.

"Geochemistry," he wrote, "is an inseparable part of cosmic chemistry." This was a new and progressive view, transferring the solution of certain cosmogonic problems from the realm of speculation into the empirical domain, based on research and new facts.

In 1933 the Soviet astronomer S. Vsekhsviatsky formulated his theory of eruptions, according to which "the small bodies of the solar system, in particular comets, arise as a result of eruptive processes on the surfaces of the giant planets". Specialists use the term eruptive to denote processes associated with eruptions, with volcanism.

In the late 1930s, a new generation of scientists began working in research institutes and observatories of our country: young people, full of bold ideas. But then the war began.

On 22 June 1941, the Second World War crossed the borders of the Soviet state and turned for us into the Great Patriotic War. Front lines cut across the country and tore apart scientific connections. Astronomers put on military uniforms and engaged in activities very far removed from observation and theoretical research. In the book Astronomy of the Twentieth Century by the well-known American astronomer Otto Struve, several names of outstanding specialists of those years are mentioned. Many observatories and their scientific staff were evacuated to the rear. But one of the most renowned scientists, Professor of Astronomy at Leningrad University K. Ogorodnikov,

volunteered to join the ranks of the defenders of the great city and remained there throughout the long blockade.

The young astronomer G. Strashny (Kharkiv Observatory — A. T.), whose work was known to Western scholars, was executed by the German occupation authorities. M. Savron, Yu. Fadeev, and A. Razdolsky, from the same Kharkiv Observatory, died of starvation.

Astrophysicists I. Timoshenko and V. Pertsov were killed with weapons in their hands. The woman astronomer Lialia Ubiivovk became the leader of a partisan detachment in the Poltava region; she was captured and tortured to death by the SS ...

This is only a small part of what the American scholar knows.

For us, the memorial lists of heroes, "who fell in the struggle for the freedom and independence of our Motherland", are much longer. Go and see for yourself. They exist at every observatory that survived the war, was destroyed, and then rebuilt after victory.

The post-war period showed an unprecedented rise in the intensity of astronomical research. Everyone understood that the old "good" times of speculative construction of hypotheses and calm theoretical interpretation of a chosen picture were gone forever. Questions of the formation and development of celestial objects could no longer be solved without knowing what these objects actually were. And so the foundations of new observatories were laid.

The successes of wartime radiolocation ensured the rapid development of radio astronomy. Astronomers gained the ability to obtain information about such distant objects and from such distances as they had previously not even dared to imagine.

From the body of the science concerned with the origin and development of celestial bodies and their systems, stellar cosmogony emerged as a distinct field, resting on the successes of astrophysics and radio astronomy. Within it a new direction was born — the cosmogony of galaxies. Even planetary cosmogony itself clearly began to branch into directions, each of which required a new approach. Thus, one of them addressed the problem of where and how the substance from which the planets formed appeared near the Sun, and in what state this substance existed. The second direction concerned the elucidation of the process by which planets formed from the primordial material. The third was interested in the initial state of the Earth. And there were also satellites, comets, and asteroids.

To construct new cosmogonic hypotheses, it was not enough merely to abandon the classical form of cosmogonic research. From now on, any newly proposed theory could not be limited to explaining the properties of a single solar system alone. Its conclusions had to be valid for billions of other stars of the Milky Way and explain the origin and existence of many other planetary systems. This was perhaps the most difficult task of all. For although there exists the view that such planetary systems are quite widespread in the Galaxy, so far no one has observed them.

Consequently, it is difficult to say which features of our solar system are fundamental and obligatory for planetary systems in general, and which are of a particular, incidental character.

By the middle of the twentieth century, all the difficulties known earlier had increased. Do you remember how we formulated the conditions of the problem for an "exact" calculation of planetary motions: "Given: 18 celestial bodies, whose positions and motions at a given moment are known ..." and so on. Then, having obtained a system of equations with two hundred and sixteen unknowns, we came to the conclusion that it was, perhaps, too difficult to solve. That referred to the situation two hundred years ago.

Today, however, in the twentieth century, the number of "legitimate" members of the solar system — without taking into account whose influence one cannot even think of an "exact" solution of the problem of their motion — has exceeded two thousand. This meant that the number of unknowns in the equations had grown to more than twenty-four thousand. And to this one must also add conditions of deformation, the influence of tides, defects in the mass of the Sun, and the increase in the masses of the planets. It is necessary to take into account the role of the interplanetary medium, electromagnetic forces, and so on and so forth. Thus now, perhaps, any attempt to resolve this problem by such a method would indeed be hopeless.

It was urgently necessary to look for a way out of the

dead end.

The Solar System As We Know It Today...

And now, before moving on to a discussion of the hypotheses of planetary cosmogony of recent years, it is worth drawing a preliminary conclusion about what we know today concerning our Solar System. New facts have accumulated. Research methods have changed. The list of features once formulated by P. Laplace has also been expanded. All this deserves to be set out, if only in order to make it possible to develop our own criteria for evaluating future hypotheses.

The Family Status of the Sun and the Composition of the Family.

At first, the author was tempted to write briefly and clearly: "The Sun has many children!" But then he stopped. If one adopts the principle of an objective account of the evolution of views on the cosmogony of the Solar System, would such a statement be correct? And if our central luminary and all the planets, planetary satellites and asteroids, comets, and entire swarms of meteoric bodies originated simultaneously from a single cloud, what sort of "fathers and children" could they be?

And so one had to settle on a more cautious definition:

> "The solar family is numerous and diverse. Apart from the Sun itself — an ordinary star — the sys-

> tem consists of a large number of the cold bodies listed above, which with enviable regularity revolve around one another and around the central body. Their total number is unknown; their total mass has been calculated only approximately and amounts to fractions of a per cent of the solar mass. Moreover, it cannot be excluded that even today not all members of the solar family have been entered into the 'ledger' of terrestrial astronomy."

Thus, the question of the composition of the family (as well as the question of its family status) can, for the time being, be answered only very vaguely.

Where Is the Boundary of the Solar System?

Unfortunately, it is also difficult to give an unambiguous answer to this question. It would seem most natural to regard the orbit of Pluto, the most distant planet, as such a boundary. Its average distance from the Sun is about 40 astronomical units — AU (let us recall that 1 AU equals 149 million 504 thousand kilometres). However, the title of "the last planet" is by no means permanently fixed to Pluto[5]. It cannot be ruled out that beyond its orbit there wander, bound by the firm chain of solar gravitation, yet another planet, or even several planets. For the time being, it is impossible to detect them.

Moreover, we already know that comets are members of the Sun's family. According to calculations, the most distant points of their orbits — *the aphelia* — lie at distances of about 150 thousand astronomical units from our lumi-

[5] In 2006 the International Astronomical Union re-defined the term "planet". Under the new criteria, Pluto does not qualify because it has not cleared its orbital neighbourhood of other bodies. It is now classified as a "dwarf planet", though it remains one of the largest and most studied objects in the outer Solar System. – DM

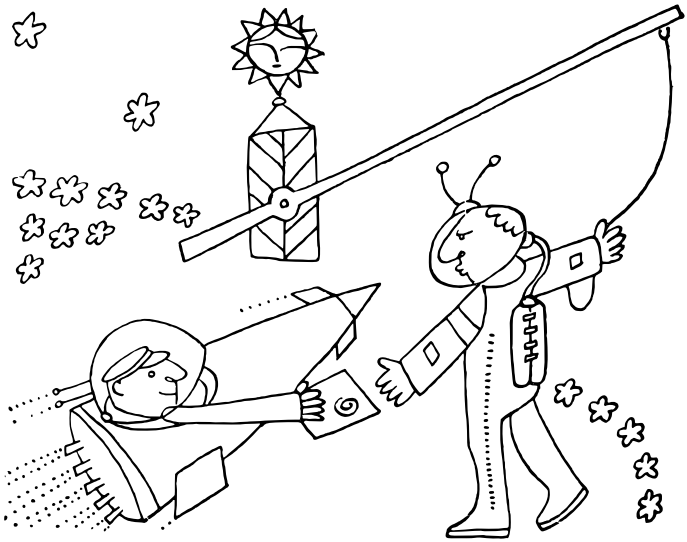
nary. This significantly pushes outward the boundaries of the Solar System, but still does not define its limit. So how far does the Sun's influence extend? The question is not a simple one, since one must also take into account the influence of all 100 billion stars of our Galaxy.

There are, however, ways to simplify the problem. If all the stars are combined into a single gravitating point at the centre of the Galaxy, and this point is considered together with the Sun and a small-mass body orbiting the Sun — such as a spacecraft — the result is a version of the three-body problem. This was solved by the American mathematician George Hill. The maximum distance at which a small-mass body can move while still remaining a satellite of one of the attracting masses is called the *Hill sphere* of that mass.

Thus, a spacecraft ejected beyond the orbits of all the planets will continue to revolve around the Sun until its distance from the luminary exceeds about 230 thousand astronomical units. This is precisely the radius of the Sun's Hill sphere. Beyond this boundary, the dominant share of the gravitational influence on the spacecraft will belong to the combined gravitating mass of all the stars of the Galaxy, which we have conventionally concentrated at its centre into a single point.

The radius of the Hill sphere is a very interesting quantity. A thoughtful reader may reflect with some pleasure on the fact that the distance to the star nearest to the Sun — Alpha Centauri — is of the order of 280 thousand astro-

nomical units. That is, it lies just slightly beyond the Hill sphere. And if there were no such "slight margin"? However, such speculations already go beyond the scope of this book.



So, an approximate boundary of the Solar System has been established. What else must be known in order to begin evaluating cosmogonic hypotheses?

Features of the Solar System.

Enumerating the principal features of the Solar System, P. Laplace wrote: "The planets move around the Sun in the same direction and approximately in the same plane."

Perhaps today this feature should no longer be stated so categorically. The inclination of Mercury's orbital plane to the Sun's equator is 7°, while Pluto's orbit is inclined by 17°8′.

P. Laplace then required an explanation of why all satellites move around their planets in the same direction as the planets move around the Sun.

This point in his list of features has fared worst of all. Since then, the inventory of planetary satellites has expanded greatly. And now, for example, four satellites of Jupiter, which have no names and are designated simply by the Roman numerals VIII, IX, XI and XII, have retrograde motion.

One may, of course, comfort oneself with the thought that the outer satellites of a giant planet are asteroids captured by its gravitational field. But what, then, is to be done with Phoebe, the ninth satellite of Saturn, discovered by W. Pickering in 1898? Phoebe also moves in a retrograde direction, but it is certainly not an asteroid. It is far more likely to be a cometary nucleus.

Five satellites of Uranus also have retrograde motion. In any case, Uranus itself is a complete riddle for cosmogony. It alone "lies" on its orbit, and moreover does so "upside down". The plane of its equator makes an angle of about 98° with the plane of its orbit.

The reason why the satellites Triton and Nereid, revolving around Neptune, have retrograde motion also remains

unclear to this day.

According to P. Laplace, the rotation of all the planets and of the Sun about their axes occurs in the same direction, and the planes of their equators are only slightly inclined to the planes of their orbits.

Alas, this statement too requires correction, since Uranus and Venus rotate in the opposite direction, and we have already spoken about the orientation of Uranus's equatorial plane.

The eccentricities of the planetary and satellite orbits known in the time of P. Laplace were very small. Today, however, this statement is no longer valid either for Mercury or for Pluto. Their eccentricities are equal to 0.20562 and 0.24864 respectively. If one compares the orbits of satellites with one another, no particular uniformity is observed here either. The orbits of Jupiter's outer satellites are fairly elongated. And as for the orbit of Nereid, there is little to be said — it closely resembles the path of a true comet. This satellite approaches Neptune to within 1 million 600 thousand kilometres and recedes from it to a distance of 9 million 600 thousand kilometres.

Only the last feature formulated by P. Laplace remains untouched: "The orbits of comets have large eccentricities and any angles of inclination to the planes of the planetary orbits." Its explanation is the subject of special hypotheses.

Features of the features.

Cosmogonists had long felt the need to create a list of

fundamental facts whose explanation would be important not only for the origin of a single solar family, but also for planetary systems of any other stars. This task is extraordinarily difficult. After all, only one planetary system is known so far. And who can guarantee that its features will prove to be a law for other systems? Nevertheless, in 1948 the Dutch astronomer D. Ter Haar published one such list, dividing all known facts into four groups.

The first group included questions concerning the regularities of orbits. For example, why are the directions of revolution of the planets and the Sun the same? Why do the orbits of planets and their satellites have such small eccentricities? Finally, why do the planes of planetary orbits so nearly coincide with the Sun's equatorial plane?

To the second group of facts D. Ter Haar assigned the regularity in the variation of planetary distances from the Sun. By this requirement he responded to the long-standing attempts of many astronomers to provide a theoretical basis for the curious, purely empirical Titius–Bode law. This well-known rule states that the distance from the Sun to any planet, expressed in astronomical units, can be approximately found from the formula

$$R_n = 0.4 + 0.3 \times 2^n \text{ AU},$$

where n is the ordinal number of the planet.

The third group of facts included questions concerning the reasons for the division of planets into two groups: terrestrial planets and giant planets. Why do the bodies of

these two groups differ from one another so sharply?

Finally, the fourth group of facts concerned the fateful distribution of angular momentum: about 98 percent is concentrated in the planets, and only 2 percent in the Sun.

Not all specialists agreed with D. Ter Haar's list. Soviet astronomers V. Fesenkov and B. Krat proposed expanding it by adding further points.

However, no list, however detailed, can encompass all the puzzling features that require explanation. Since the launch of the first artificial Earth satellite in 1957, the era of space exploration by satellites and interplanetary

spacecraft has brought new information almost daily. Modern cosmogonic hypotheses must therefore explain not only the physical differences between terrestrial planets and giant planets, but also the peculiarities of their motions. Why, for example, do Mercury and Venus rotate so slowly, while Jupiter, Saturn, Uranus, and Neptune rotate extremely rapidly?

No satisfactory explanation has yet been found for the abundance of asteroids and meteoroid bodies within the Solar System. Are these remnants of "construction debris", or fragments of a once-existing planet, Asteroidia, that disintegrated? Both hypotheses have their supporters and their critics.

Closely related is the mystery of Saturn's rings. How, and by what processes, did nature succeed in creating this unique phenomenon?

However, to discover peculiarities and mysteries one does not even need to strain one's eyesight. The Moon, it would seem, is known to everyone. People have even been there. And yet what the Moon actually is — a satellite or an independent celestial body — is still unknown to anyone. For the Earth–Moon system is unique. None of Earth's "relatives" has such a relatively large satellite. How, then, are we to imagine the mystery of its origin?

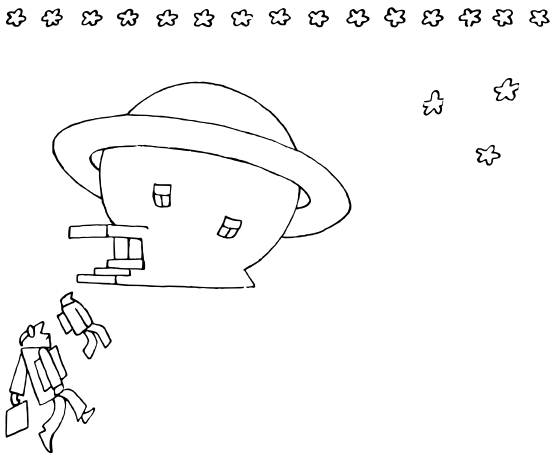
There are many facts. From them one could probably compile an entire book, giving it a title in the spirit of the past century — "*Mysteries and Unresolved Questions of the Planetary System*" — or, conversely, in a modern style

— "*The Solar System: Yesterday, Today, Tomorrow*".

At present, the study of the Solar System has entered a new phase — the phase of direct investigation. The radiation belts of the Earth have been discovered, as well as unexpected details of the structure of the atmospheres of Venus and Mars. Radio waves have brought new information about Mercury and Jupiter to Earth. Instruments installed on spacecraft have made it possible to refine the mass of Jupiter and have confirmed that this planet emits approximately 2.5 times more thermal energy than it receives from the Sun. All this must be taken into account by cosmogonic hypotheses. However, it turns out that the new information so far contributes not so much to the creation of new hypotheses as to the destruction of old ones — one after another, one after another...

It is precisely the description of this process that the following sections of planetary cosmogony will, apparently, be devoted to.

6 Fresh Currents of Cosmogony: Hypotheses, hypotheses, hypotheses...



The Hypothesis of K. Weizsäcker

The year 1943 began very unhappily for Hitler's Reich: The Russians are still defending," said the staff. But the generals knew that the Soviet troops were not only defending. Crushed," in the Führer's conviction, they had grown stronger and had long been striking the "invincible" soldiers of the Wehrmacht.

Admittedly, this had very little to do with astronomy — but it did have some connection. It did because astrologers and other "masters of occult matters" had long been sneaking about Hitler's headquarters like mice. For some time, charlatans in black uniforms, and others without uniforms but with golden party badges on their collars, had been running German science. Yet fidelity to ideas alone is poor fuel for the locomotive of progress.

Thus the Nazis tried to make use of Germany's true scientists for their "cause." Orders from the Reich Chancellery forbade engaging in problems that would not yield effective results within six months. Naturally, such problems received no financial support. But what could be done with theorists, whose work required only a sheet of paper, a pencil, and a mind? Paper and pencil could not be taken away. In the civilisation that existed, these were always available. What remained... the mind? But there were far too many minds. They could not manage them all in time.

In 1943, Karl Friedrich Weizsäcker was thirty-one years old. Karl Friedrich did not wear boots with flared tops,

the kind that made it convenient to tuck in magazines for a submachine gun. Weizsäcker was an astronomer and spent his free time developing a new cosmogonic hypothesis. What path did he choose? After all, both the nebular and catastrophic hypotheses had sufficiently discredited themselves in recent years...

K. Weizsäcker did not attempt to invent anything new. He returned to the views of Kant and Laplace, supporting the idea of bodies condensing from a rarefied mist. The nebular hypothesis again?

Yes, the nebular hypothesis! But not "again." The criticisms of Jeans–Jeffreys' hypothesis were still too fresh for anyone to risk defending a catastrophic idea. It was different with the work of Kant and Laplace. Much water had flowed under the bridge since then. Perhaps recent advances in physics could provide a plausible mechanism for the condensation hypothesis?

K. Weizsäcker turned for help to the theory of turbulence, developed in the very latest years. Specialists use this term to describe a phenomenon observed in many liquids and gases. It consists in the fact that speed, temperature, pressure, and, most importantly, density experience random chaotic deviations from their average values — *fluctuations*. This means that all these characteristics could change irregularly from point to point over time in an initially uniform cloud. Consequently, separate vortices could arise in the flat disc of the primordial nebula.

In a popular review published after the war in an Amer-

ican astrophysical journal under the names of G. Gamow and D. Hynek, it was stated:

> "... these vortical motions are analogous to the rotation of balls in a bearing. If the outer ring of the bearing (the vortex) moves clockwise, and the inner ring counterclockwise, then the balls will rotate in the 'forward' direction; as is the case with the planets."

The principle of the "mechanism" can be easily understood by the reader from a diagram, drawn from a fully authoritative source.

At the points where neighbouring vortices meet, as the diagram shows, particles collide, stick together, and gradually form planets there.

> "Planets grew by accreting small fragments of condensed heavy elements. Satellites formed in a similar way within smaller nebulosities surrounding the planets; the direction of satellite orbits and planetary rotation is explained by convective currents,"

wrote K. Weizsäcker.

In his view, the theory of turbulence should explain not only the features of the Solar System noted by P. Laplace, but also the spatial distribution of planets, the arrangement of their orbits, and the distribution of angular momentum.

The theory of the German astronomer was well received by specialists. However, in 1945, there prevailed throughout the world a somewhat enthusiastic atmosphere of post-war optimism. True, criticisms of it were voiced

from the very first days. Yet, according to G. Gamow and D. Hynek, the main merit of the new work was that "Weizsäcker introduced a fresh current into the stagnant swamp of theories on the origin of the planets."

The Hypothesis of O. Yu. Schmidt

In 1944, two of Otto Yulyevich Schmidt's first articles on the cosmogonic hypothesis of the Solar System were published in the *Reports of the Academy of Sciences of the USSR*. Until the end of his life, Academician O. Schmidt continued to develop this hypothesis, assembling a large creative team of young talented astronomers and mathematicians.

Interest in his work was immense. When, on 31 January 1947, he decided to present a paper at the plenary session of the Second All-Russian Geographical Congress, the academy was truly besieged by people. Not only the conference hall but all adjoining rooms were filled to capacity. People held their breath as they listened to Schmidt's somewhat husky voice, reporting on the "*New Theory of the Origin of the Earth and the Planets*." What, then, was the main idea of his hypothesis?

Once, perhaps several billion years ago, a solitary star — the Sun — encountered on its path through the universe a large gas-and-dust nebula. Such clusters are fairly common in space, and meeting them is not as unique as, for example, encountering another star. As a result of this

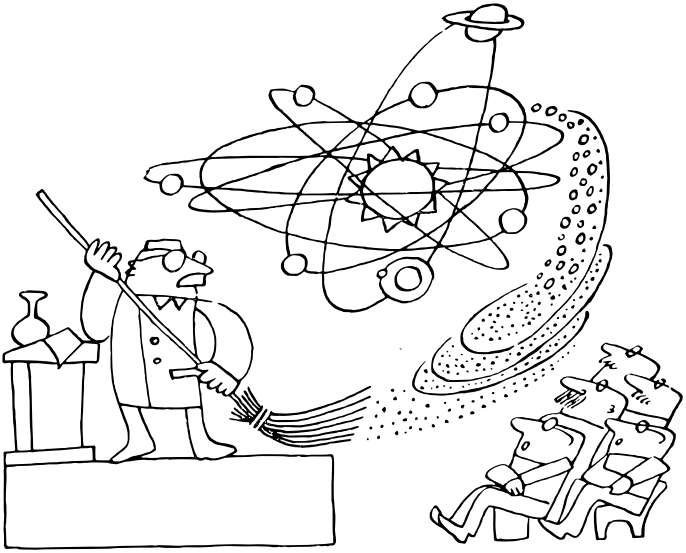
encounter, a significant portion of the nebula followed the Sun. The excess of its speed relative to the nebula imparted to the diffuse matter an angular momentum not associated with the rotation of the star itself.

By the laws of nature, the cloud began to rotate, flatten, and contract. Individual particles began to merge, forming larger bodies. Soon, it was no longer a gas-and-dust cloud but a dense stream of meteoric bodies orbiting the Sun. Meteors collided and stuck together. In regions close to the Sun, dense clumps of the future planets revolved. Further from the life-giving heat, these clumps incorporated lighter substances, including frozen gases. In this way, the Solar System was formed.

O. Schmidt was not a professional astronomer. Nor was the very idea of the Sun encountering and subsequently capturing a gas-and-dust cloud during its motion around the centre of the Galaxy new. Many had discussed and written about this at the end of the previous century and the beginning of this one. O. Schmidt carefully studied the hypotheses of his predecessors, taking from them the rational elements.

From I. Kant he adopted the idea of a dust cloud, of dust particles as the raw material for the formation of planets, and the notion of the "cold" origin of the Earth.

From P. Laplace — thoughts on the role of gas condensation in the formation of planets, the analogy with nebulae observed in our Galaxy, and the idea of compression and densification of a rotating nebula.



From F. Moulton and T. Chamberlin he took the idea of planetesimals as a transitional form in planet formation.

From J. Jeans — the idea that the angular momentum of planets could be imparted from outside as a result of the Sun encountering another celestial body.

"Yet, despite this," writes V. Bronshtein in the book *Conversations on Cosmos and Hypotheses*, "Schmidt's hypothesis bore no resemblance to any previously proposed hypothesis and was not a compilation of them. This hypothesis was entirely independent."

The new hypothesis turned out to be excellent. It easily

addressed a number of difficulties encountered by other authors and explained the main features of the Solar System rather well. But it also had weaknesses. One of these was the very assumption that the Sun could capture part of the gas-and-dust cloud it encountered.

Here we must again turn to the laws dictated by celestial mechanics. These laws state that a solitary star cannot, in principle, capture a solitary nebula. This was proven when solving the "two-body problem."

Let us imagine: in empty, infinite space there are two bodies. Let one be the stationary Sun — body *A* — and the other a nebula passing by — body *B*. Under the influence of gravitational forces, the trajectory of body *B* is deflected and becomes a hyperbola. But the branches of the hyperbola extend to infinity.

For the nebula (body *B*) to be captured, it must first be slowed down, to convert its hyperbolic orbit into an elliptical one. However, the Sun alone cannot achieve this. Even if the nebula initially had no velocity and the two bodies approached each other under the influence of their mutual attraction alone, capture would still be impossible. A nebula arriving from infinity would simply swing past the Sun along a parabolic trajectory and continue off to infinity again. No, other conditions are required for capture. What if we consider not a two-body, but a three-body problem?

Such a problem, however, had already been solved more than ten years earlier by the French mathematician Jean Chazy. According to his solution, even in a three-body

system the capture of one body by another is impossible. O. Schmidt did not believe Chazy. Setting out the initial conditions, he began calculations. When a first estimate suggested that perhaps he, rather than Chazy, was correct, he passed the problem to P. Parisky — the same famous mathematician who had decisively disproved Jeans' hypothesis through numerical calculation. Parisky did not disappoint. In his very first report, O. Schmidt confidently spoke of the possibility of capture in a three-body system.

Nevertheless, although this scenario had a higher probability than Jeans' star–star encounter, it was still highly artificial. This is why the hypothesis of gravitational capture came under such severe criticism at the first conference on cosmogony.

O. Schmidt's thoughts were entirely absorbed by this problem. In 1951 he turned sixty. Friends presented the birthday celebrant with a playful verse:

> On the brink of the world's abyss
> He sat with a long beard
> And gazed into the distance...

Thus the poem began. It went on to give a rhymed description of the mechanism of his hypothesis and ended with a lament over the unresolved problem of capture:

> And before the new theory
> Even Laplace would bow his head,
> Were it not that the debate
> Over the role of capture
> Continued among us.

And the debate over the mechanism of gravitational capture continued unabated. Although a number of astronomers proposed their own original solutions to this problem, most specialists leaned towards the idea of the Sun and the protoplanetary cloud forming together. In this aspect of the problem, matters gradually returned "full circle," back to the framework of the classical hypothesis.

The single cosmogonic problem of the origin of the Solar System was broken into parts. Specialists, having despaired, left aside the questions of how and from where the Sun acquired its nebula, and turned instead to discussing the stages of evolution of an already-formed cloud around an already-formed Sun.

Of course, a complete picture could not be obtained in this way, but perhaps it would be possible to develop a theory of the "mechanism" by which planets form from dust and gas.

Much work on tasks related to this partial approach to the problem of the Solar System's origin was undertaken by a group of researchers at the Institute of Physics of the Earth of the USSR Academy of Sciences under the leadership of B. Levin. Very interesting and productive research was carried out by L. Gurevich and A. Lebedinsky in Leningrad.

In the process of working on his hypothesis, O. Schmidt demonstrated a model of the modern style of science. Thus, having begun alone, he soon worked with a team of specialists from a wide range of disciplines. This gives us

the right to consider his theory the first truly collegial work in the field of cosmogony.

In books one can read about all manner of attitudes towards O. Schmidt's cosmogonic theory. As a rule, both the "pro" and "contra" arguments are equally convincing. One cannot disagree with the observation that considering the process of the formation of the planetary system with a fully formed Sun, while neglecting the evolution of the central star, is hardly justifiable. It would be more appropriate to regard the problem of planetary cosmogony as intimately connected with the questions of the origin not only of the Sun but of stars and stellar systems in general.

The capture hypothesis also failed to provide a satisfactory explanation for the alignment of the rotation of the Sun and the planets, or for the small deviations of the orbital planes of the major planets from the Sun's equatorial plane.

Schmidt's hypothesis likewise did not satisfactorily explain the distribution of planets by distance. Nor did it account for the uniqueness of the Earth's satellite — the Moon.

For many, even the central thesis of Schmidt's theory — the formation of the Earth from cold particles — was questionable. Advocates of early heating of our planet argued that physico-chemical, not merely gravitational, processes must have played a significant role in the Earth's evolution. Yet it is difficult to imagine such processes operating in a cold coma of initially coalesced material.

Specialists were also dissatisfied with the fact that Schmidt's hypothesis "could not predict a single previously known feature of the Solar System, which indirectly indicates the unconvincing nature of its main propositions."

These criticisms were formulated by the astronomer S. Vsekhsvyatsky.

All these shortcomings were no secret to those who had spent many years developing Schmidt's hypothesis. Why, then, did they not stop? Why did they not abandon all those incredibly tedious — and apparently fruitless — calculations midway? Perhaps they were not so fruitless after all. Remember, we have already noted that in science nothing is wasted, provided one does not count plainly unscientific nonsense.

The theoretical problems of the capture theory, diligently worked on by specialists in celestial mechanics, suddenly proved to be an invaluable contribution to the developing field of astronautics. You may ask: how? Here is how.

Imagine that we need to launch an automatic interplanetary station (AIS) to Mars or Venus[6]. To escape the maternal embrace of Earth's gravity, the carrier rocket must impart to the spacecraft a third cosmic, or "hyperbolic," escape velocity from Earth. But the greater the required speed, the more powerful the rocket engines must be. And there is problem number one! That costs money!

Is it not possible, somehow, to outwit nature and launch,

[6] In Soviet terminology an "automatic interplanetary station" (AIS) referred to an uncrewed planetary probe. Beginning in the early 1960s, the USSR launched a series of such missions under programmes such as *Venera* (to Venus) and *Mars*. Several Venera spacecraft successfully entered the Venusian atmosphere and transmitted data from its surface, while Mars probes achieved flybys, orbiters, and limited lander operations. These missions formed a major part of the early robotic exploration of the Solar System during the space race. – DM

for example, a spacecraft so that, travelling towards Mars at an obviously insufficient speed, it passes by the Moon, which, by its gravity, adds velocity and directs it precisely in the required direction? But what has this to do with cosmogony, you may ask?

The point is that the problem of the "gravitational slingshot" of a spacecraft is the closest theoretical relative of the very problems addressed by the theory of capture. And you may believe that the accuracy of Soviet AIS missions to Venus and Mars owes much to the theoretical work in cosmogony. Just as the flights of American probes to Jupiter, using a gravitational manoeuvre at Mars, and to Mercury, with a gravity boost from Venus, also relied on such theoretical foundations.

The Hypotheses of G. Gamow and J. Oort

K. Weizsäcker, in his work, made extensive use of the achievements of theoretical physics, yet he still had to leave certain questions unaddressed. At first, these seemed trivial, mere details. The main point was the conception of the entire "mechanism" of the formation of the planetary system from a cloud of diffuse matter.

It was precisely these details that drew the attention of the American physicist G. Gamow. In the post-war years, he rightly ranked among the ten best scientists in America. He advised the Manhattan Project, worked on the problem of the origin of chemical elements, and wrote and lectured

extensively, satisfying the suddenly awakened interest in science among the military, journalists, and the general public. His broad erudition, vivid imagination, and lively writing style enabled him to move from individual refinements of Weizsäcker's hypothesis to a detailed picture of planetary formation.

The reader will probably remember the German cosmogonist's remark that the primordial nebula, like the Sun, must have contained very few heavy elements. G. Gamow clarifies and develops this point. In his view, the nebula consisted mainly of hydrogen, followed by helium and dust. Such a mixture, even "very dilute," must have a certain viscosity. This means that, as it rotated according to a separator-like principle, the light gases would be pushed out from the central regions and soon move entirely to the periphery of the Sun. There they would condense, adhere to solid particles, and form clumps — embryos of the future giant planets.

Gamow even calculated the speed of this evolution. To form clumps one centimetre in diameter from the "liquid jelly" of the primordial nebula would take only a few years. After a hundred million years, the diameter of a formed clump could reach that of Jupiter.

In the central near-solar region, the picture is different. There, particles moving along Keplerian orbits would collide frequently. Some would stick together, while others would vaporise... It is clear that in the central region, the clumps would be denser, without frozen gases.

This described "sorting" of the primordial matter also determines the differences in the chemical composition of terrestrial planets and giant planets, as well as the character of the distribution of their masses with distance from the central star. In this way, Gamow neatly resolves features that had long been a "stumbling block" in the path of previous hypotheses.

The picture painted by G. Gamow was vivid, full of inner drama, and highly convincing. Yet, alas, even his cosmogonic recipes could not satisfy all the demands of specialists. From time to time, a dark cloud would appear on the astronomical horizon. A "newly observed" feature of the Solar System constantly failed to fit into the proposed theoretical scheme.

For example, even in K. Weizsäcker's hypothesis there was no satisfactory explanation for the origin of comets. Their diversity could not be reconciled with a single mechanism" of formation. Perhaps they were intruders altogether, having wandered to us from the stellar spheres" by chance?

These celestial wanderers, so feared in past centuries and now contemptuously called "apparitions," were most surprisingly divided into short- and long-period comets. The former posed no mystery, since their aphelia clustered near the giant planets, and their origin could reasonably be associated with those planets. But the second group...

The director of the Leiden Observatory, Professor J. Oort (incidentally, from 1966 a foreign member of the USSR

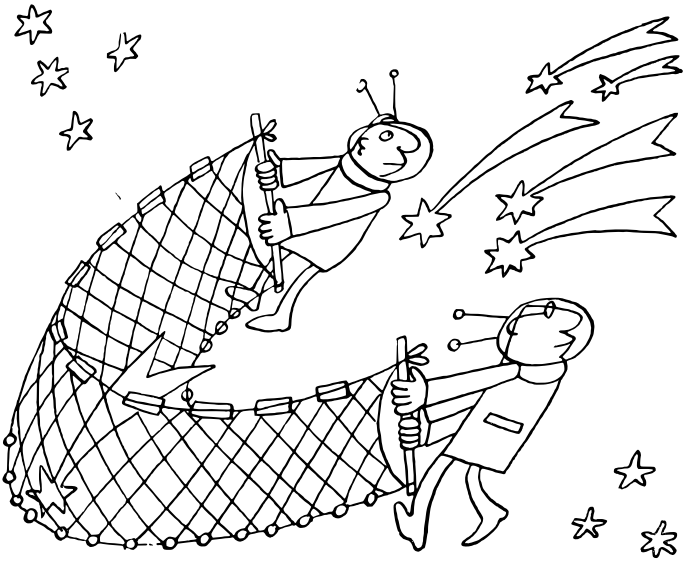
Academy of Sciences), gathered an enormous amount of information on long-period comets. He tabulated the values of the semimajor axes of their orbits and discovered that most have a value of roughly 150,000 astronomical units. Could it be that these "intruder" comets are delivered through interstellar space? No, Oort was convinced that they are members of the Solar System, travelling together with our star through the universe.

But what, then, are 150,000 astronomical units? Oort revived an old idea, first suggested by the nineteenth-century Italian astronomer D. Schiaparelli, of a cometary cloud surrounding the Solar System. He gave it an elegant mathematical form, asserting that 150,000 astronomical units is nothing other than a critical distance. Recall the Hill sphere. If the semimajor axis of a comet's orbit exceeds this limit, the main disturbing force ceases to be the Sun and becomes the stars. Their influence can be so great that they are fully capable of drawing distant wanderers out of the bounds of the Solar System. Stars also affect the gradual movement of the most distant comets, altering their orbits so that they enter the inner region and become visible from Earth.

Oort's hypothesis explained many features of the cometary family. Moreover, the results of his theoretical conclusions agreed with the calculations of observers.

Oort considered the source of comet formation to be a possible explosion of a planet-like body whose orbit once lay between Mars and Jupiter. Some fragments thereby ac-

quired roughly circular orbits, lost their original gas under the action of sunlight, and became ordinary minor planets and meteorites. Others, which acquired elliptical orbits, were subjected to the perturbations of many planets.



Even if one assumes that most of them were lost into space, enough must have remained to form the outer cometary cloud. These fragments could retain ice, ammonia, and methane, because at such large distances (on the order of 100,000 astronomical units) the Sun's light is many times weaker than on Earth, and its rays are unable to produce irreversible changes in a comet's composition.

Perhaps for the first time, Oort's hypothesis more or less tied the loose ends concerning the origin of comets and gave them a place within the overall cosmogony of the Solar System.

The Hypothesis of J. Kuiper

K. Weizsäcker's hypothesis had a significant influence on many foreign cosmogonists. The American astronomer J. Kuiper, of Dutch origin, also began developing a hypothesis from 1949 onwards, in which, as with Weizsäcker, only gravitational forces were considered. Kuiper believed that the Sun formed as a result of the contraction of a dense cloud of interstellar gas. Around the newly formed star, a nebula in the form of a disc with a radius of several tens of astronomical units was preserved. From this building material, large Weizsäcker-type vortices formed large, loosely bound protoplanets.

However, Weizsäcker also postulated smaller intermediate vortices, which helped to explain the direct rotation of the planets. In Kuiper's model, there were no intermediate vortices, and the large ones caused the protoplanets to spin in the opposite direction. To account for this discrepancy, he was forced to introduce additional assumptions.

Kuiper called the protoplanets "large" because he believed that up to 99 per cent of their mass would have been lost under the influence of the Sun's corpuscular radiation before they were finally formed. The harsh "solar wind"

simply "blew away" this mass from the loosely bound protoplanets. This, he argued, explained why the terrestrial planets close to the Sun are so markedly deficient in hydrogen compared with the more distant giant planets.

According to Kuiper, the Earth most likely was never in a molten state. Its heating may have occurred through the decay of radioactive elements. Nevertheless, in the earliest stages of its existence, our planet may have been elastically soft.

He regarded Saturn's rings as the remnant of the nebular disc that surrounded the planet during its formation.

Kuiper believed that the origin of satellites is no different from that of planets. The Moon, whose age he estimated at no less than a billion years, is an independent cold celestial body. In recent years, however, this view has undergone some revision, and Kuiper now favours the hypothesis that volcanism played an important role both in the history of the Moon and in the development of other celestial bodies.

The Hypothesis of E. Epik

Around the same years that J. Kuiper was developing his theory, the astronomer Ernst Epik was working at the Tartu Observatory in Estonia. In 1960, his work was published in New York, in which he likewise attempted to depict a cosmogonic picture.

Epik was not concerned with the origin of the primordial nebula. As his starting point, he took the existence of the Sun and a pre-existing nebula around it. In other words, it was "given." Because of its rotation, the nebula was non-uniform. In the plane of the ecliptic, denser bands of dust formed, which completely absorbed the Sun's light. The evaporated gases, entering this region of near absolute zero, condensed, formed snowflakes, and froze onto the dust particles, creating planetesimals.

The planetesimals coalesced into protoplanets. And the greater their mass became, the faster planetesimals collided with them, releasing increasing amounts of heat.

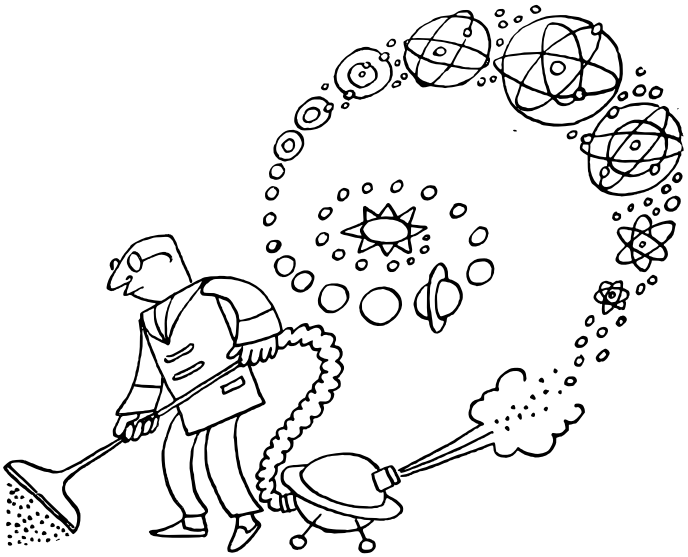
The future planet — Epik takes the Earth as an example — heated up: ice melted, gases evaporated and escaped into space, while heavy stony and metallic particles remained, forming the solid body of the planet.

Today there is much discussion about climate change on Earth. One of the causes specialists cite is the greenhouse effect, meaning that, due to severe atmospheric pollution, the Earth's heat radiation is slowed and the overall temperature rises. According to E. Epik, the greenhouse effect also played a significant role at the beginning of Earth's history, when our planet was surrounded by dense dust. The dust acted as a barrier to the radiation of heat from the Earth.

Our planet must have heated to a molten state. In the liquid Earth, dense and light substances separated: metals sank to the core, while rocky lava, oil, and water rose to the surface. Gradually, the space around the Earth cleared of dust, and the planet began to cool, despite the heat of the Sun's rays. This is how the astronomer E. Epik pictured the formation of the Earth.

He did not agree with J. Darwin's conclusions regarding the Moon, believing that the satellite had formed near the Earth as an independent celestial body. Epik considered the lunar craters to be solely the result of meteorite impacts, rejecting the possibility of volcanic activity on our satellite. All the sadder, then, was the report from the Soviet astronomer N. Kozyrev, who observed an eruption in one of the lunar craters. Of course, the report could

have been questioned. But following Kozyrev, American astronomers also observed signs of volcanic activity on the Moon. Finally, the first astronauts to orbit the Moon saw a reddish glow in the lifeless mountains.



It is not so easy, even with sufficient data, to construct a hypothesis that satisfactorily answers all the questions. It seemed that the classical approach — relying solely on gravitational forces to explain the formation of the planetary system — was finally reaching its limits.

The Hypothesis of H. Alfvén and F. Hoyle

As early as 1912, C. Birkeland attempted to introduce electric and magnetic forces into the cosmogony of the Solar System. His first attempt was not very convincing. Of course, if one takes into account that the primordial nebula must have consisted of a mixture of charged particles, the Sun, thanks to its powerful corpuscular radiation and magnetic moment, could indeed act as a "separator," and gradually layers or rings composed of different ions could form around it. Accepting the mechanism proposed by Birkeland, one might expect that all the planets would differ sharply from one another in composition. But then, why do meteorites falling on Earth have a composition so similar to it?

After the end of the Second World War, the Swedish astrophysicist Hannes Alfvén proposed a hypothesis in which planets formed mainly as a result of electromagnetic forces.

H. Alfvén began from the assumption that the Sun once possessed a very strong magnetic field. The nebula surrounding the star consisted of neutral atoms. Under the influence of radiation and collisions, the atoms became ionised. The ions were caught in traps formed by magnetic field lines and carried along by the rotating star. Gradually, the Sun lost its rotational momentum, transferring it to the gaseous cloud.

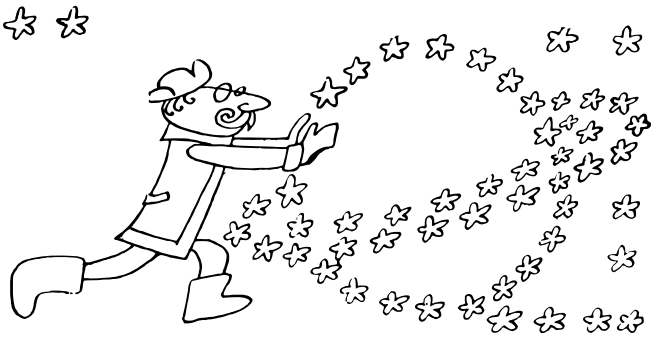
The difficulty with this hypothesis lay in the fact that

the atoms of the lightest elements would be ionised closer to the Sun, while those of heavier elements would be ionised further away. Therefore, the planets nearest the Sun should consist of the lightest elements — hydrogen and helium — while the more distant planets should be composed of iron and nickel. Alas, observations show the opposite.

Nevertheless, it became clear to all scientists that electromagnetic forces must have played an important role in the formation of the Solar System. At this point, the English astronomer F. Hoyle developed a new version of the hypothesis. Initially, it followed the pattern proposed several times before. The Sun formed in the depths of the nebula. It rotated rapidly, and the nebula gradually flattened, forming a disc. The disc itself then began to accelerate, while the Sun slowed. Angular momentum was transferred to the disc. Planets then formed within it.

"Stop! Stop!" the reader might say. One cannot describe the essence of the new hypothesis like this. There is nothing new or unexpected here — just the usual skeleton of the nebular hypothesis.

Correct! The novelty lies in the details, above all in how the transfer of momentum occurred. This is where, according to F. Hoyle, magnetic forces come into play. If one assumes that the primordial nebula already possessed a magnetic field, the redistribution of angular momentum could indeed take place. Hoyle demonstrated this.



But what about the differences in planetary densities, which X. Alfvén's hypothesis failed to explain? Hoyle allows that the momentum is transferred from the Sun not to all particles of the nebula, but only to the gaseous ones. This is understandable, as they are more easily ionised. He writes:

> "By acquiring angular momentum, the planetary material moved away from the solar condensation. The non-volatile substances condensed and lagged behind the outward-moving gas. It is this process that explains the fact that the terrestrial planets:
>
> 1. have low masses;
> 2. consist almost entirely of non-volatile sub-

stances;
3. are located in the inner part of the system."

F. Hoyle considered that such a mechanism creates the conditions for the existence of a rocky–metallic zone near the Sun, which, over a broad interval between the orbits of Mars and Jupiter, gives way to a region dominated by water and ammonia. There, at the level of Jupiter and Saturn, snowflakes and frozen ammonia coalesce, gathering around themselves a large amount of uncondensed gas.

Jupiter and Saturn fit this scheme well. The density of Saturn, being further from the Sun, was, as expected by the hypothesis, lower than that of Jupiter. But what about the even more distant planets — Uranus and Neptune — whose densities rise again? Hoyle proposed a new mechanism: at this level, in the cold of interstellar space, water and ammonia freeze, while hydrogen escapes into interstellar regions. Only the heavier hydrocarbons can then concentrate here.

The second part of F. Hoyle's hypothesis, which explains the mechanism of planet formation, is far less convincing than the part concerning the formation of the protoplanetary nebula. Here, its creator is forced to make a number of artificial assumptions, which diminish the credibility of the whole picture.

Hoyle was also unable to provide a satisfactory explanation for the satellite problem. In his view, all satellites formed as a purely hydrodynamic process, as had already been described previously, without any participation of

electromagnetic forces. Hence the shortcomings. The hypothesis could not account for observed differences in satellite systems — for example, why Mercury and Venus have none, while the Earth has its unique Moon. It also failed to explain the differing tilts of planetary rotation axes, particularly the anomalous orientation of Uranus. In short, even the partial inclusion of electromagnetic forces has so far failed to fulfil expectations.

The Hypothesis of S. Vsekhsvyatsky

There is yet another curious hypothesis in planetary cosmogony. Its author is the well-known Soviet astronomer S. Vsekhsvyatsky. He relies on the assumption (unfortunately, only an assumption) that the principal role in the evolution of the Solar System throughout its existence has been, and continues to be, played by explosive volcanic or eruptive processes.

The beginning of this so-called "eruptive hypothesis" of Vsekhsvyatsky is very interesting. As we have already discussed, one of the pressing problems in cosmogony is the origin of asteroids, comets, and the various wandering fragments and cosmic dust scattered through space. P. Laplace, when speaking of comets, had already suggested that they form in interstellar space and from there intrude into the confines of the Solar System.

Later, this problem was discussed by many prominent mathematicians and astronomers. The idea that wander-

ing celestial bodies were captured by the Sun was called into question. All the comets then known were declared to be the original property of our star. Yet the question remained: where had they come from?

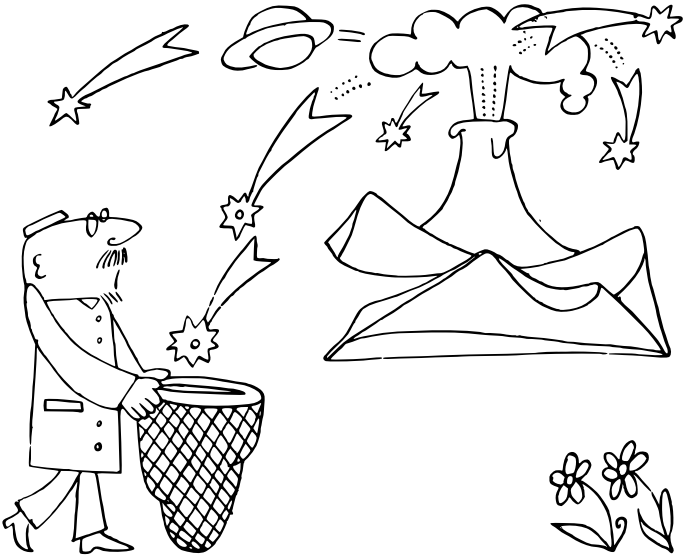
The failure of interstellar space as the source of this "apparent nothingness" led the astronomer G. Olbers, already in the previous century, to suggest the existence of a once "special" planet that had broken apart, giving rise to all the wandering bodies of the Solar System. Later, J. Schiaparelli attempted to demonstrate that beyond the orbit of the last known planet there exists a vast cloud of comets surrounding the entire Solar System. This idea was subsequently developed, as we have already seen, in the work of J. Oort.

In the middle of our century, R. Littleton suggested that comets condense from cosmic dust, which enters certain "regions of gravitational focusing" within the Sun's field of attraction. However, the laws of mechanics demanded that small particles in a gravitational field should disperse rather than concentrate.

In general, many specialists pondered the problem, calculated orbits, and pondered again... Some orbits clearly indicated that their comets had emerged from the Sun's interior. This suggested that explosions and outbursts of our star periodically eject matter into space, matter destined to form comets and meteor masses. Moreover, calculations showed that some comets could be grouped into families with an unquestionable connection to the giant planets.

All this led S. Vsekhsvyatsky to return to the idea, once

proposed by P. Lagrange, that cometary matter is ejected as a result of the volcanic activity of planets.



You may say, all this is fine, but how can the volcanic hypothesis for the formation of comets be adapted to the origin of the entire Solar System?

And here is the hypothesis! Let us suppose (once again "suppose"; truly a magical and indispensable word in cosmogony; without it, these specialists would long ago have been deprived of their daily bread) that our Sun was once a binary star (the idea is not new, if we recall). Let us further suppose that, at some moment, the second component

of the Sun exploded! Why it exploded — the hypothesis does not say. There is no need to guess either. Stars "love to explode; such is their nature," we might say in the spirit of Aristotle.

Thus, after the explosion, the dispersed matter of the second star began to gather into clumps, from which the protoplanets later formed. And since the masses of the newly formed celestial bodies were already insufficient to ignite, and then sustain, thermonuclear and other reactions in their interiors, the protoplanets began to cool rapidly, losing gases and light elements, and became covered with a crust. Indeed, stubborn geologists insist that terrestrial rocks were never molten, but we have uttered the magical word "suppose". From time to time, gases broke through the fragile planetary crust and were ejected into space, carrying away part of the matter. During these eruptions, some planets lost more of it, others less. Thus, from initially roughly similar protoplanets, planets with different physical and chemical compositions were formed.

S. Vsekhsvyatsky's idea of the role of explosive processes as a mechanism for the formation of the primary protoplanetary cloud and small bodies of the Solar System is interesting. Yet the subsequent development of the planets in his model largely follows already established evolutionary pathways, and therefore, in addition to its own shortcomings, carries the burden of the defects of previous hypotheses.

At this point, it may be sufficient to limit ourselves to

a listing of the hypotheses of planetary cosmogony. Not because the "horn of creative abundance" has run dry. No, there are still many hypotheses. But some of them differ from those already known only in minor details, or require the use of mathematical apparatus to appreciate these distinctions.

A Time to Build and a Time to Destroy...

Many hypotheses have been constructed by classical cosmogony. What unites them is a single general characteristic — *deductiveness*.

The ancients called deduction the derivation of consequences from premises given in advance, naturally in full accordance with the laws of logic. Therefore, using deduction, proceeding from the general to the particular, one can effectively test hypotheses and examine the content and essence of observed phenomena. Yet, without the aid of the logical method of reasoning from the particular to the general, known as induction, pure deduction can never provide a comprehensive understanding of objective reality. This was noted even by the classics of Marxism–Leninism. In *The Dialectics of Nature*, F. Engels wrote: "Induction and deduction are connected in the same necessary way as synthesis and analysis," for, ultimately, "any deductive conclusion depends on observation, experiment, and induction."

If we look back at the path traversed by planetary cos-

mogony, which was briefly outlined in the preceding sections of this book, it is easy to see that after the collapse of J. Jeans's hypothesis, this branch of science fell into a profound crisis. The decisive role in creating this situation was played by new facts obtained through observation. The very foundation underpinning all existing hypotheses came into contradiction with the facts. And to bring the science out of this crisis, scientists had to revise the foundation laid in the very formulation of cosmogonical problems and seek new methods for solving them.

Previously, no one had challenged the preconceived notion of the initial state of matter in any system as a rarefied nebula. This seemed self-evident, though it was not supported by any substantial observational data. And this a priori assumption determined the further speculative method of deductive constructions. However, it was entirely justifiable. Observations from the surface of the Earth, despite the best efforts of astronomers, could not provide sufficient astrophysical data on which an inductive method of constructing hypotheses could be based. The Moon was distant. Mercury was poorly observable due to its proximity to the Sun. Venus was perpetually hidden beneath a shroud of impenetrable clouds of unknown origin. Myths about Mars filled numerous gaps in knowledge, creating a quasi-plausible picture. It is enough to recall how many "communications with Martians" projects were presented, or to recall the serious work of astrobotanists, who identified the spectra of Martian seas and canals with those of Earth vegetation. Jupiter and Saturn were debated. The

other planets were scarcely considered at all.

Everything has changed over the past scarcely twenty years — the first years of the Era of Human Space Exploration. Look today at the map of the lunar hemisphere facing the Earth. It can astonish any imagination with its "settlement." Many dozens of points of spacecraft landings cover the surface of the Earth's satellite. Dozens! This is not to mention that Soviet automatic stations circled the Moon and photographed its "far side," and delivered two self-propelled research vehicles to its surface. Finally, in December 1972, the sixth and last, and longest, manned expedition to the Moon under the *Apollo* programme was completed. The list of planned work was quite extensive, and astronauts J. Cernan and H. Schmitt, having landed in the Taurus–Littrow valley, remained on the Moon for approximately 75 hours. The most interesting find is considered to be a large area of orange-coloured surface discovered near the Shorty crater. H. Schmitt, a geologist by profession, believes this is the result of soil processing by gases typically released from a volcano before the end of an eruption. This is an important conclusion for determining the historical past of our satellite.

Approximately one month after the American visit, on 16 January 1973, at 4:14 a.m., on the eastern edge of the Sea of Serenity, within the Le Monnier crater, the second Soviet research rover, *Lunokhod-2*, descended from the landing stage of the *Luna-21* station.

Over five lunar days, the automatic rover covered a

distance of 37 kilometres, transmitted 86 panoramas and more than 80,000 television images of the lunar surface to Earth. All noteworthy details of the relief were recorded using stereoscopic imaging.

The information obtained by specialists through direct study of the Moon will greatly contribute to the accumulation of new data not only about the origin of the Moon and the Earth, but also of the entire solar system.

Interesting data on the study of outer space were obtained by scientists using instruments installed on board the Soviet automatic *Prognos* stations. Three spacecraft, launched during 1972–1973, were intended for a comprehensive study of solar activity and its influence on physical phenomena in interplanetary space, the Earth's magnetosphere, and atmosphere. The instruments aboard the Prognos stations recorded the largest solar flares in the past 20 years. These findings will aid in a better understanding of the nature of solar activity and provide deeper insight into the mechanisms of Sun–Earth interactions.

Soviet interplanetary automatic stations traversed distances of millions of kilometres, penetrated the cloud layer of Venus, and descended onto its heated surface, revealing to astonished observers the unforeseen appearance of Earth's "sister planet." American automatic stations followed the Soviet missions. One of them even proceeded further towards the Sun and circled Mercury, transmitting information about the planet back to Earth.

Soviet and American automatic interplanetary stations

reached Mars, entered "Mars-centric orbits," and during the period of the great opposition dispelled many of the legends about the Red Planet, replacing them with authentic knowledge. The descent module of the Soviet station landed on the surface of Mars and transmitted information directly from "Martian soil."

In recent years, active collection of direct information about members of the solar system has begun. This development ensures a new, more productive approach to solving cosmogonical problems — the accumulation and systematic synthesis of factual data.

At the end of 1972 and the beginning of 1973, the space communication antennas at Goldstone (USA) were directed at Saturn. After an almost ten-year hiatus since the radar studies of the nearer Jupiter, a similar experiment was conducted with the distant Saturn. However, no reflected signal was received from the planet itself. The main reflected signals came from the rings. Their analysis suggests that the rings consist of blocks of solid material with diameters of one metre or more, with irregular surfaces and sharp protrusions. The density of the blocks in the inner ring is apparently greater than in the outer ring.

Nevertheless, this is the result of one method of signal analysis. Another approach, assuming that the returned radio waves underwent multiple reflections within the ring material, requires a sharp reduction in the estimated size of the blocks. Some specialists even consider that Saturn's rings consist of a scattering of particles with diameters of

less than one centimetre. This example of the difficulties encountered in interpreting experimental results can serve as an illustration of the "reliability" of such information.

On 3 March 1972, at 1:49 Greenwich Mean Time, from the Kennedy Space Center, a three-stage *Atlas-Centaur* launch vehicle placed the spacecraft *Pioneer 10* onto its designated trajectory to Jupiter. Nine months later, *Pioneer 10* made its flyby of the giant planet at a minimum distance of 130,000 kilometres. The scientific instruments on board the spacecraft transmitted information about the state of the near-planet environment of Jupiter, as well as images of Jupiter and its four largest satellites.

Processing the received data on electronic computing machines also took approximately nine months. What new knowledge did this information provide? As a result, specialists constructed a new model of the king of planets. We now understand Jupiter as a rapidly rotating gas sphere, composed primarily of hydrogen (82 percent) and helium (17 percent). Its solid core, if it exists, must be very small. At the planet's centre, the temperature reaches approximately 30,000 degrees. Under the influence of intense thermal radiation and the planet's rapid rotation, the gaseous masses of Jupiter's clouds have stretched into multicoloured bands. The grey-white zones represent ridges of relatively warmer masses, while the orange-brown bands correspond to colder troughs in the cloud layer. The famous "Great Red Spot" appears in photographs as frozen vortices of a colossal storm, towering above the main cloud layer.

Curious information also came from Jupiter's satellites. All four of its large moons appear to have an atmosphere, composed primarily of hydrogen. Television images revealed the rippled surface of Ganymede, reminiscent of the appearances of the Moon and Mars. The density of the satellites, however, delivered a pleasant surprise to supporters of classical cosmogony. The innermost moons, Io and Europa, have a density close to that of the Moon, suggesting they are composed primarily of rocky material. The more distant Ganymede and Callisto appear to be a mixture of ice and rock. Thus, the density of the satellites decreases with distance from the primary planet, in accordance with the classical principles of cosmogony.

On 6 April 1973, from the same spaceport, the duplicate spacecraft *Pioneer 11* was launched towards Jupiter. On 2 December 1974, the craft passed the planet at a minimum distance, three times closer than *Pioneer 10*. Its instruments photographed and transmitted to Earth images of the planet itself and three of its satellites. Notably, Callisto displayed a clearly visible polar cap. As this satellite lies outside Jupiter's intense radiation belts, it is conceivable that Callisto could serve in the future as a base for long-range space travel. On the closer moons, the radiation environment is hazardous to human life.

Subsequently, through a manoeuvre, *Pioneer 11* shifted to a new trajectory and set course for Saturn. If all went well, it was scheduled to encounter the second giant of the Solar System on 5 September 1979. The probe was to pass fairly close to Titan, Saturn's moon, which exceeds

Mars in size and is believed to possess a relatively dense atmosphere.

After its encounter with Saturn, *Pioneer 11*, like *Pioneer 10*, was to continue beyond the limits of the Solar System.

Specialists are particularly interested in any details regarding Jupiter, as the planet remains surrounded by many mysteries. Some scientists even consider it a kind of "Rosetta Stone" of the Solar System. Recall that in 1799 the French military engineer A. Bouchard, supervising the construction of trenches near the city of Rosetta, discovered a dark basalt slab inscribed in three scripts, including ancient Egyptian hieroglyphs. A few years later, this allowed the Englishman T. Young and the Frenchman J. Champollion, working independently, to decipher the hieroglyphs. Scientists hope that information from Jupiter will serve as a similar key to understanding the origin and evolution of the Solar System.

The trajectory of *Pioneer 10* is directed towards the star Aldebaran, with an estimated travel time of roughly 1,600 years. *Pioneer 11* has no such precise destination yet. It is difficult even to predict with certainty what these Earth emissaries might encounter on their journey. What if one of them were ever intercepted by intelligent beings from another stellar system? This possibility was anticipated. Both spacecraft carry "letters": gilded aluminium plates, on which explanatory illustrations are securely etched. In the upper-left corner of the plate is a point representing

the Sun, from which lines extend to fourteen pulsars. Specialists believe that these "radio beacons" can be detected by any intelligent civilisation in the universe capable of observing them. Next to each pulsar, in binary code, is a number corresponding to the pulsar's emission frequency at the time of the spacecraft's launch. Since pulsar frequencies decrease according to a known law, extraterrestrials could, by knowing the launch frequency, readily calculate in the future when the message was sent.

On the left is shown a diatomic hydrogen molecule — the most abundant element in the cosmos. The wavelength of its radio emission (21 centimetres) is taken as the standard unit for all measurements in the message. On the right, against the outline of the Pioneer spacecraft, are depicted the nude figures of a man and a woman. Beside them is a line 21 centimetres long and the number eight in binary. By multiplying 21 by 8, extraterrestrials could calculate the height of humans and compare it with the size of the spacecraft.

At the bottom of the plate are depicted the Sun and a row of nine planets. From the third planet, a trajectory extends past Mars, around Jupiter, and then into interstellar space.

The authors of the message place little hope on success. Yet, as the American astronomer C. Sagan said, "the chances of communication with intelligent beings from other worlds will always be zero" if no attempt is made. It is hard to disagree with this.

Today, many examples of a new approach to cosmogonical problems can be cited. Criteria of scientific truth are beginning to emerge, which hypotheses must satisfy. For instance, in explaining phenomena, a hypothesis must not contradict the laws of nature and must adhere to the principle of correspondence, which enshrines the continuity between old and new theories.

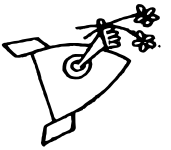
Then, since every hypothesis deals with a hidden mechanism of phenomena that cannot be directly tested, the hypothesis itself must satisfy the condition of fundamental testability.

An important criterion is also the extent to which a hypothesis not only explains the narrow set of phenomena for which it was devised, but also predicts new data.

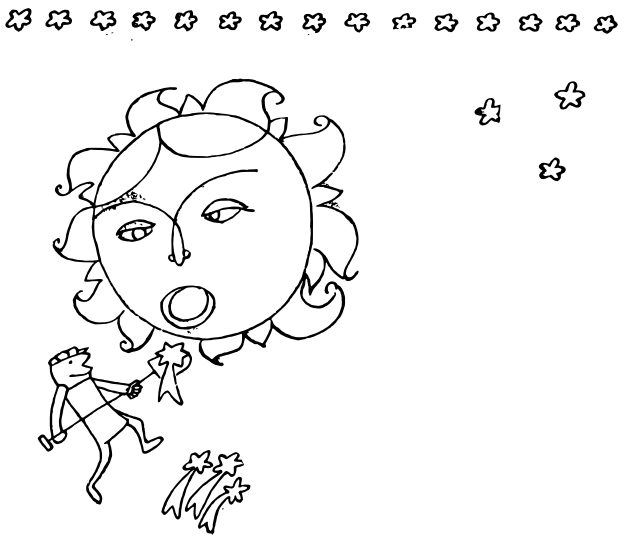
Finally, based on a single foundation, each hypothesis should explain diverse phenomena without invoking additional assumptions.

At present, planetary cosmogony lacks a single overarching idea accepted by an absolute majority of specialists. It is difficult to say what will come next. Perhaps a new unifying hypothesis will emerge on a classical basis, or perhaps on a new one. Perhaps the astronomers who claim that understanding the origin of the Solar System is impossible outside the framework of a general theory of stellar development will be proven correct. Or perhaps "a synthesis of competing hypotheses, theories, and concepts in cosmogony will occur."

In conclusion, it should be noted that there remains an as yet uncharted field for the application of youthful energy and enthusiasm, armed with knowledge.



7 Stellar Cosmogony: Two Concepts



It is probably appropriate to begin by noting that in contemporary science dealing with the origin and evolution of stars and stellar systems there exist two sharply defined, opposing, and mutually antagonistic directions. One of them is old and classical, based on the nebular principle, that is, the view that stars are formed from rarefied diffuse matter through the gradual contraction of an initial nebula.

The second direction is new and is led by the Soviet school of Academician V. Ambartsumian. It proceeds from a directly opposite view, namely that stars and stellar systems are formed as a result of the fragmentation of massive and dense (and perhaps even superdense) bodies.

Such a pronounced split within the camp of cosmogonists speaks first of all of a certain crisis in the science itself: the accumulated evidence has outgrown the old speculative hypotheses, yet remains insufficient for the convincing confirmation of the new ones.

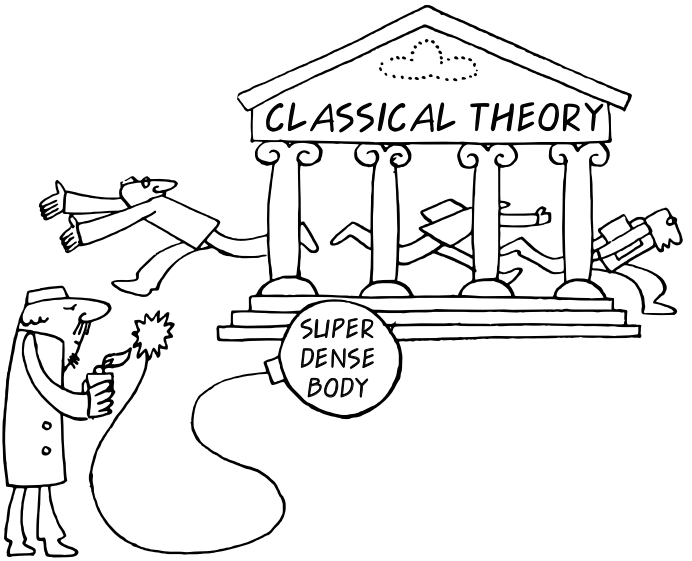
The difficulty lies in the fact that, in a number of cases, the same facts can be explained with equal success from the standpoint of theories that mutually exclude one another. This situation is not new for astronomical science. One may recall how, in the fifteenth century, celestial phenomena were explained simultaneously from both Ptolemaic and Copernican positions, and how, owing to the youth and insufficient development of the new theory, the Ptolemaic algorithm often proved to be more accurate.

It is therefore not excluded that stellar cosmogony today is in a state close to that which astronomy experienced

five centuries ago.

On the side of the classical hypothesis stand tradition and solid mathematical theories.

On the side of the hypothesis of V. Ambartsumian stand a new way of looking at the problem and a whole series of successfully predicted new facts that find no satisfactory explanation within the framework of the old theories.



In recent years, thanks to the rapid development of new technology, astronomers have obtained a great deal of data on very different phases of cosmogonic processes in the Galaxy and beyond it. Yet none of these data allows one to

say with certainty: "Look, this is the formation of a young star!"

Moreover, new observations have made it possible to draw a directly opposite conclusion: that the dominant processes in the Universe are not condensation, merging, and concentration, but rather explosions, decay, and disintegration. These results led to the creation of a new concept of dense (and super-dense) protobodies that serve as sources of star formation. However, although such objects ought to be highly impressive even on the scale of the metagalaxy, astronomers have so far been unable to detect a single one of them by direct observation. So what should one believe? To which viewpoint should one give the palm of priority?

There is no need to speak any further about "belief in science", but as for the "palm of priority" ... Perhaps, as often happens, the truth lies somewhere in between? Perhaps. But so far it has not been found. And in order to understand what the dispute is really about, it is probably necessary to refresh our memory of the subject itself and first recall what stars are, what we know about them with certainty, and by what principles we, as humans, attempt to classify them.

An Ordinary Star – the Sun

"...The Sun is the only star in which all phenomena can be studied in detail," wrote the American astronomer George

Ellery Hale, who received the Gold Medal of the Royal Astronomical Society for his method of photographing the Sun's surface and for other works. There is no reason to doubt the truth of this statement even today. And although, in describing the Sun and the stars, we intrude into the realm of astronomy and even astrophysics, we have no other choice. The Sun is indeed a typical, ordinary star and can quite reasonably serve as a standard — a criterion — for the other luminaries.

Long ago the ancient sages proclaimed: *Ex nihilo nihil fit* — "nothing comes from nothing". A fine slogan of the materialist view of the world. Was it not from this that the great idea of the conservation of matter and energy arose, becoming a cornerstone principle of science? As early as Mikhail Vasilievich Lomonosov used to say, weighing his retorts with chemical mixtures: "If something is taken away from one thing, then just so much is added to another..."

Observing the Sun, William Herschel more than once pondered how much fiery energy our luminary gives off into the surrounding space. It gives energy away — but where does it take it from? Herschel aptly called this question "the great mystery". He did not find an answer to it and set it aside, turning to other observations.

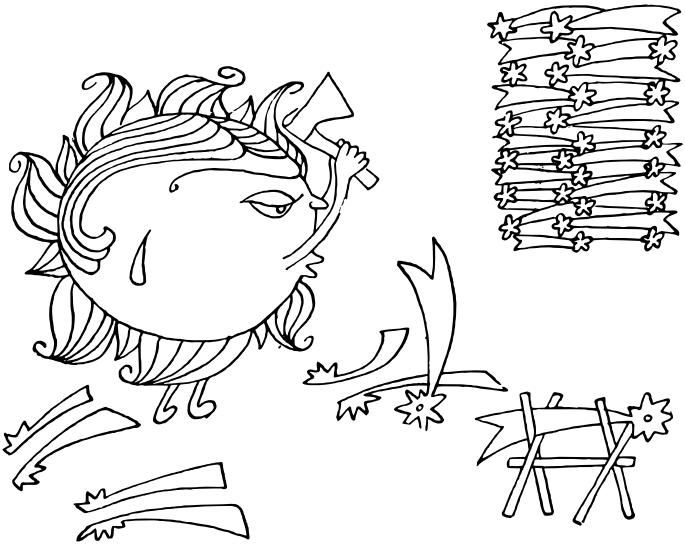
The modest Heilbronn physician Julius Robert Mayer never imagined that he would become the cause of one of the fiercest controversies among such eminent figures of nineteenth-century science as R. Clausius, W. Thomson (Tait), W. Rankine, J. Joule, and E. Dühring. Still less could he

have foreseen being honoured with a comparison made by E. Dühring in the title of an article, "Robert Mayer — the Galileo of the Nineteenth Century". What, then, made the former ship's doctor, who lived modestly and in obscurity in the provinces and from time to time wrote demanding scientific papers, so famous?

In the papers of Dr. Mayer

- there was a new view of forces.
- the first law of thermodynamics was formulated for the first time.
- a definition of the mechanical equivalent of heat was given.

It was precisely this circumstance that became the subject of a bitter dispute among the venerable authorities. A dispute not about the substance of the discovered law, but, alas... about priority; a dispute over who was first: R. Mayer or J. Joule.



A universal law of nature, admitting of no exceptions, states that the production of heat requires a certain expenditure of force. But this force, however varied it may be, can always be reduced to two principal categories: the "expenditure of chemical material" or the expenditure of mechanical work. Consequently, the source of solar heat must be sought in one of these two corresponding agents, and a choice must be made between them.

Further on, R. Mayer gives several illustrative examples. He assumes the Sun to be composed entirely of coal and shows that, in that case, it would be completely burned up in 4,600 years. He converts the energy of the Sun's rotation

into heat and shows that, in this case, it would suffice for only 158 years. But

> "... the matter appears in an entirely different light if one considers the Sun as a link in the universe. Through our solar system, in addition to the planets known so far with their eighteen satellites, there pass numerous comets, which, according to the famous saying of J. Kepler, are more numerous in the heavens than fish in the ocean; to these must also be added the asteroids, which, judging by the shooting stars and fireballs we observe, are beyond counting. Therefore, from all sides a limitless stream of ponderable matter must slowly but continuously flow towards the Sun and, colliding with it, transform the mechanical force of its motion into heat."

Such was the first formulation of the meteoritic, or "dynamic", theory of the Sun.

H. Helmholtz carried out calculations and obtained interesting figures. A reduction of the Sun's diameter by only one ten-thousandth would be sufficient to compensate for thermal losses for more than two millennia.

The theory of H. Helmholtz was opposed by the engineer Karl W. Siemens, a member of the large firm Siemens and Halske, founded by his brother Ernst.

K. Siemens lived in England, where he adopted the name William, and was known as a supporter and promoter of all kinds of regenerators for steam engines, regenerative furnaces, regenerative condensers, and the like.

Economical, like all Germans, W. Siemens could not tolerate the fact that the lion's share of solar energy is lost in world space and only an insignificant part is used beneficially to heat the planets. In order to remedy this situation, he proposed a hypothesis that purported to explain the return to the Sun of the heat it had expended. To this end, he filled all of world space with gases, naturally in a rarefied state. Each celestial body, by the force of gravity, creates for itself an atmosphere from these gases. Its lower layers consist of heavy gases, the upper layers of light ones, for example combustible hydrogen.

Now let us imagine a gigantic solar sphere, violently rotating in space. From its equator, under the action of centrifugal force, enormous masses of heavy gases must be torn away and fly off. At the same time, through the poles, streams of new light and combustible gas will flow in, which, by burning, will compensate for the Sun's losses due to radiation. W. Siemens proposed a model of the Sun in the form of a kind of regenerative furnace, in which liquid matter is restored from the products of combustion. A hypothesis that seems strange from modern perspectives nevertheless enjoyed success. F. Rosenberger, the author of the substantial work History of Physics, wrote in 1892: "The theories of the conservation of solar energy presented here [7] do not contradict one another, contain nothing implausible, and may coexist side by side. At the present moment the most lively of them is the theory of Siemens, but the most grandiose, without doubt, is that of Mayer, since it links our system with the other bodies of

[7] (that is, the hypotheses of R. Mayer, H. Helmholtz, and W. Siemens. — A.T.)

the universe and promises the preservation of the solar system until the universal end, that is, until the equalisation of energy throughout the entire universe."

An interesting quotation, if one reflects on it. Once, while studying the operation of steam engines, S. Carnot came to the conclusion that even in the complete absence of friction no machine that converts heat into work can have a one-hundred-per-cent efficiency. The reason is that part of the heat, and therefore of the thermal energy, inevitably passes from the boiler to the condenser, heating the latter. Consequently, a portion of the energy will always be lost, raising the temperature of the condenser. This will continue until the temperatures of the boiler and the condenser become equal, after which the machine will cease to operate. From this, S. Carnot arrived at the second principle of thermodynamics, later generalised by R. Clausius and W. Thomson. Today this law is formulated as follows: "In a closed system, all processes lead to an increase in entropy." Entropy is a measure of the degradation of energy.

The Solar System can also serve as an illustration of this law. In accordance with the formulated principle, evolution proceeds in only one direction. Consequently, in the end there is always death. But if there is existence in between, there must also have been a beginning, that is, a birth. Let the birth of the Solar System be due to the manifestation of cosmic forces. But what if the second principle of thermodynamics is extended to the entire world? Who created it? It seems that, however one turns it, one cannot

manage without God. Such is the conclusion to which this seemingly harmless quotation leads us.

Many outstanding scientists of the nineteenth century spoke out against the idea of the "heat death of the universe". Today, fears of this kind are of purely historical interest. The twentieth century in general put an end to speculative conclusions that had often appeared in the past as scientific hypotheses. A new era proposed new methods. In order to move forward, it was first necessary to generalise the accumulated information. The continuous advancement of hypotheses, by contrast, resembled running in place.

The Sun Without Hypotheses And The Theory Of "Thermonuclear Fusion"

What do we know about the Sun today? Let us compile something like a medical record for our luminary – similar to those produced in endless numbers for us in clinics instead of simply sending us to a sanatorium. Only facts, without any conjectures or hypotheses.

First of all, the angular diameter and the distance to the Earth. Both quantities are easy to measure. Next, the amount of solar radiant energy falling on a unit area of the Earth's surface per unit time. For this measurement it is best, of course, to go to the equator. But if you do not wish to travel there, the experiment can be carried out at home at noon. Further, by comparing the colour of the

Sun with the colour of heated substances on Earth, we can indirectly judge the surface temperature of the luminary. And by studying the age of the oldest terrestrial rocks, we can roughly estimate the lower limit of the Sun's age. After all, it is hardly reasonable to assume that the Earth is older than the Sun.

If we also add the orbital period of the Earth (or any other planet), which is needed to determine the mass of the Sun, together with a set of data that defines our luminary as a member of the Galaxy, then this essentially exhausts all observable characteristics. One might also add, for example, the rotational speed of the Sun calculated from the motion of its spots, but here there is a difficulty. First, sunspots are visible only in the belt from +40° to –40° of heliographic latitude; at higher latitudes they are hardly noticeable. Second, the Sun rotates differently at different levels — faster at the equator and more slowly closer to the poles. Which speed, then, should be taken as the principal one?

Observed Characteristic	Value
Angular Diameter	31′59″26
Distance From The Earth	149 504 000 ±17 000 km
Solar Constant	$1.39 \cdot 10^6$ erg s^{-1} cm^{-2}
Surface Temperature	6000 K
Age	$(4.5 - 6) \cdot 10^9$ years
Earth's Orbital Period (Sidereal Year)	365.25636 days
Inclination Of The Solar Equator To The Ecliptic	7°15′
Velocity Of The Sun Relative To Surrounding Stars	19.5 km s^{-1}
Distance Of The Sun From The Galactic Centre	8000 parsec = 2450 LY
Velocity Of The Sun Around The Galactic Centre	250 km s^{-1}
Orbital Period Of The Sun Around The Galactic Centre	$1.8 \cdot 10^8$ years

Using these data, after carrying out certain calculations, one can compile another table — incidentally, one that is far more important than the first from the point of view of astrophysicists.

Calculated Characteristic	Value
Mass	$1.983 \cdot 10^{33}$ g
Mean Density	1.41 g cm^{-3}
Total Radiation (Luminosity)	$3.78 \cdot 10^{33}$ erg s^{-1}
Diameter	1 390 600 km
Volume	$1.412 \cdot 10^{15}$ km^3
Gravitational Acceleration At The Solar Surface	$2.738 \cdot 10^4$ cm s^{-2}
Critical Velocity (Escape Velocity)	619.4 km s^{-1}

And finally, for comparing the Sun with other stars, astrophysicists have introduced several additional characteristics.

Characteristic	Value
Apparent Visual Stellar Magnitude	$-26^m.80 \pm 0.03$
Absolute Photovisual Stellar Magnitude	$+4^m.96$
Spectral Class	dG2

The letter *m* in the exponent denotes the stellar magnitude, which determines the brightness of a star. The letter *d* before the spectral class indicates that our star is a dwarf.

Of course, these are far from all the characteristics. They have also been selected by the author in a rather arbitrary manner.

However, once they have been presented, it would be appropriate to explain why they are so important in a book devoted to questions of cosmogony — precisely cosmogony, and not astrophysics or stellar astronomy. And

here is why.

The minimum age is the time during which our luminary has practically not changed. The evidence for this is provided by the terrestrial strata.

The average density — 1.4 g/cm^3 — indicates that the solar globe consists of a rather rarefied substance.

And the acceleration due to gravity — 28 times greater than on the Earth — testifies to a powerful external effect. And immediately the question arises concerning the nature of a celestial body that can exist for so long and under such conditions. What is it like? Solid? No. The density is too low. Liquid? No again. Perhaps gaseous? That is quite possible. After all, physicists do say that only internal thermal pressure can prevent our luminary from undergoing immediate contraction. And this pressure arises due to the thermal motion of the particles of solar matter. Hence, the Sun is a gaseous sphere, and moreover a very hot one.

Look at what an extraordinarily original conclusion we have managed to reach...

Excellent. Now one may turn to thinking about those reactions that for so long and so steadily sustain the life of our luminary, and with it our own fragile existence. Helmholtz's assumption of energy arising from contraction is unsuitable. On that basis the Sun could have remained in its present state for no more than a few million years. That is insufficient. Nor is it worth speaking of chemical energy: in that case the timescale would be even shorter.

Then what kind of energy is it?

In the unofficial history of physics one episode has been preserved. It is told that once two friends — cheerful physics students from the illustrious University of Göttingen — were strolling through a shady park on a hot sunny day. Passing from tree to tree, they laughed and said that in such weather a case of sunstroke among some of the professors could not be ruled out, which in itself would not be such a bad thing, since then tomorrow's lectures would be cancelled. However, a true physicist cannot even speak about sunstroke without forgetting physics. Today it is difficult to reconstruct which of the students was the first to arrive at the idea of the true source of energy of the Sun blazing overhead. In any case, it is unlikely that anyone will blame us if we imagine the scene somewhat further...

> — I swear by the report that has to be handed in tomorrow, this... — Fritz Houtermans, for that was the name of one of the students, gestured towards the Sun, — this is not a bonfire made of beech logs.
> — Quite so, — his friend took it up, — it would have gone out long ago, and today there would not be such insane heat.

F. Houtermans's friend was called Atkinson. He had just arrived from Cambridge, where everyone was fascinated by E. Rutherford's remarkable experiments on atomic transformations. Perhaps half in jest, he suggested that the Cavendish atomic transformations, which were giving rise to such heated debates, and the intense processes inside the Sun must have some connection. F. Houtermans seized

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> — Of course, light elements fuse, form heavier ones, and the released energy scorches our heads...

Perhaps it was precisely from this casual conversation that the serious work of both physicists on the problem of the theory of thermonuclear processes in the depths of the Sun began. Many teeth and spears were broken over it. To assume that the energy of the Sun is due to the fusion of hydrogen atoms and the formation of heavier helium was far too little. It was necessary to prove that this hypothesis rested on solid ground. For the synthesis of light nuclei, a monstrous temperature is required. Does the Sun provide the necessary conditions with only about six thousand degrees on the surface?

"What do you mean, only?" the reader familiar with the achievements of electric and gas welding technology may reasonably take offence. "We would be glad to have such a temperature!" That may be so. It would be fine for us, but thermonuclear reactions have no use for it. For "thermonuclear fusion", six thousand degrees is cold. At such a temperature, reactions refuse to proceed. So what is to be done about the source of solar energy?...

Here, the problem was approached from a completely different angle by Arthur Stanley Eddington, a remarkable English astronomer and astrophysicist, who did a great deal both for science itself and for its popularisation.

After Pyotr Nikolaevich Lebedev discovered and measured light pressure, none of the physicists, generally speaking, knew what to do with this pressure. Many believed that such a negligible force could not play a significant role in the life of cosmic celestial objects. But A. Eddington

built his theory of stellar equilibrium precisely upon it. He was one of the first to arrive at the idea that where energy is emitted on cosmic scales, light pressure, together with ordinary gas pressure, can balance the gigantic force of gravity generated by the enormous mass of a star. While working on his theory, A. Eddington considered whether mass itself influences the physical state of the incandescent gaseous spheres that we call stars. This thought grew stronger, turned into conviction, and in the end, confirmed by theory and observation, became an important cosmogenic law.

There is no need to list all the scientific works of A. Eddington, President of the Royal Astronomical Society. Many of them lie outside the limits set by the subject of our book. What is important for us to know is that, using the derived relations and knowing the mass, and hence the gravitational attraction of the Sun, A. Eddington calculated the pressure required to balance the forces of gravitation, and then the temperature in the interior of our luminary capable of providing the required pressure.

The result was a truly astronomical figure of fifteen million degrees. The reader, even one accustomed to the large numerical scales of our time, cannot help but catch their breath. Especially when one considers that, according to the most recent calculations of our own day, this figure has risen even higher and exceeded twenty-one million.

The calculations of A. Eddington reconciled physicists with astronomers.

There was now enough heat to "incubate" a thermonuclear fusion reaction. All that remained was to choose an appropriate type of such a reaction. The point is that one can write down quite a large number of them. But since all the data of spectral analysis spoke with one voice, insisting that the Sun consists almost entirely of hydrogen and only slightly of helium, the German physicist Hans Albrecht Bethe, who had been working in the United States since 1939, tried to adapt for the Sun reactions of thermonuclear synthesis of helium from hydrogen through intermediate transformations. He wrote them down. He checked them. They seemed to fit. The rates at which the reactions proceeded fully ensured the total amount of radiation. Then H. Bethe rewrote his equations and modestly admitted to his colleagues that it appeared he had discovered the only source of solar energy possible so far.

His colleagues were surprised that this had not occurred to them themselves. They were delighted that Bethe's work left room for further refinement of the theory and rushed, competing with one another, to realise these possibilities.

Today, Bethe's ideas lie at the foundation of the classical theory of stellar evolution. They have been developed so thoroughly that one must be a very bold person to raise a voice against them. Many predictions of the theory have been confirmed by observations. And H. Bethe himself received the Nobel Prize in 1967.

Now it is time to ask the main question, after which the

last doubts should disappear:

> "And how did experiment, direct experiment, confirm Bethe's hypothesis? After all, hydrogen bombs have exploded above the Earth more than once, both above and below..."

Alas! As the saying goes, "there is still no direct experimental proof of the thermonuclear nature of solar energy." Moreover, theorists have already calculated not one, but several mutually consistent models of the Sun. This is a rather discouraging fact. One would prefer just one. But for that it is necessary to know with certainty what is inside the Sun. And for the time being, any precise information about the solar core is lacking. After all, even Herr H. Bethe, when proposing his profound theory, relied only on "surface" data. This, of course, refers to data from spectral analysis. Astrophysicists would seemingly give a great deal to be able to look, even with one eye, into the interior of our star...

If H. Bethe is right, then it is possible to imagine the conditions inside the Sun. Nuclear reactions in the centre generate powerful gamma radiation which, forcing its way through the thickness of solar matter, is transformed into longer-wavelength radiation — *X*-rays. However, the depths of our star are equally opaque to both gamma and *X*-ray radiation. And therefore the latter, rising ever higher and closer to the surface, undergoes yet another transformation it turns into radiation of still longer wavelength, that of visible light. Only after this do the rays leave the Sun and, a little more than eight minutes later, kindly provide terres-

trial observers with all the information contained within them. But only about the region that produced them — the surface of the Sun.

What is to be done then? Light rays are unsuitable; radio emission and *X*-rays that reach us from our star also carry no information about the deep interior. And yet there is a way out! Internal reactions produce yet another type of radiation — neutrino radiation. And for neutrinos, whether it is the Sun, the Earth, or empty space, it is all the same. They pass through them almost unhindered, interacting with nothing. Might it be worth trying to catch them?

In 1964 the American physicist R. Davis began such experiments. Workers in the consumer services sector would have gone mad with envy had they known how many canisters of a colourless liquid used for cleaning clothes were lowered into one of the shafts of a remote gold mine. However, R. Davis had no intention of setting up an illegal — or rather underground — dry-cleaning operation. A gigantic tank filled with tetrachloroethylene was meant to capture solar neutrinos. And the physicists went underground in order to avoid unnecessary background from other particles.

The idea of the experiment was to catch solar neutrinos that could reveal information about the processes occurring inside the Sun. Unfortunately, despite three years of work and continuous improvement of the measurement techniques, the neutrino detector (or "neutrino telescope") stubbornly showed a particle flux ten times smaller than

expected from theoretical calculations. There was every reason to fall into despondency.

It is said that, trying to console R. Davis, the workers remarked: "Do not be upset, doc. This summer has been so cloudy..." However, jokes helped little. What was evident was a glaring contradiction between experiment and the accepted theory. The theoreticians, however, did not remain despondent for long. They immediately proposed a multitude of saving hypotheses, among which, naturally, were some that concealed violations of certain fundamental laws of nature or were based on such ultra-novel assumptions about the existence of phenomena that no one had ever observed. The authors of these works were not troubled by the fact that hypotheses of this kind found little success among serious specialists.

A simple and promising path towards solving the neutrino deficit problem was proposed by the American astrophysicist W. Fowler of the California Institute of Technology. He drew his colleagues' attention, first of all, to the fact that in principle there is a large difference between the neutrino flux and the light flux (the flux of photon luminosity, if one speaks scientifically). Neutrino particles are not impeded by solar matter and therefore, having been born in the interior of the star, they can already be in the mine, in the tank with dry-cleaning liquid, a little more than eight minutes later. Light, however, is quite another matter.

Before that same wave of thermonuclear energy which

has just produced the neutrinos we have caught reaches the surface of the Sun and gives rise to photons, a fairly long time must pass. Physicists call it the "Kelvin–Helmholtz time". There is no single agreed opinion about its duration. W. Fowler considers it to be approximately thirty million years. Other specialists are convinced that it is smaller by about a factor of three... But in any case, the appearance of photons must lag quite significantly behind the appearance of neutrinos born of the same process.

Of course, our Sun is a rather calm star ("touch wood, lest we tempt fate"). But changes may nevertheless occur in its centre. What kind? W. Fowler speaks, for example, of mixing. Yes, fairly rapid mixing of the inner hot layers with the outer, cooler ones. As soon as this occurs, the temperature at the centre of the Sun falls. And the number of high-energy neutrinos depends very strongly on temperature. Hence the neutrino flux drops sharply. In time, of course, the light flux will also decrease. But not immediately...

It follows that, if such mixing were to occur in the solar core, terrestrial instruments should register a decrease in the neutrino flux within a matter of minutes. Meanwhile, the light from the Sun would continue to pour down upon us for a long time in an unchanged amount.

Before the printer's ink had even dried on the pages of the journal in which W. Fowler published his hypothesis, specialists from research groups in the United States and England, who had computers and appropriate pro-

grammes for calculating stellar processes at their disposal, had already begun their calculations. This indicates that the question of solar reactions is now extraordinarily acute.

It is still too early to assess the results of these calculations. In many respects they diverge from one another. But that Fowler's idea is fruitful is doubted by no one.

However, another question may arise: why should the solar interior suddenly begin to mix at all? For the time being, most astrophysicists prefer not to express an opinion on this matter. But quite recently, in one article signed by theoreticians from the Cambridge Institute, F. Dilke and D. Gough, a hypothesis concerning possible causes of such mixing was nevertheless proposed. Its essence was that, over approximately every 250 million years of "quiet life", too much "slag" accumulates in the interior of the Sun. The chemical composition of the substance changes so much under the influence of the reactions taking place there that a breakdown occurs, a mixing which lasts for roughly a million years or less. Naturally, after such an event, as after a heart attack, the Sun requires up to about ten million years to recover, after which a period of calm life once again sets in.

Computer calculations show that during mixing there should be a sharp increase in the neutrino flux, after which its intensity drops just as sharply and then, over a long period, gradually rises again, approaching the normal level.

Now let us imagine that relatively recently mixing occurred in the interior of the Sun. Our instruments should

record a reduced neutrino flux (as happened in the experiment of R. Davis). And the light? The light we shall continue to receive from the Sun in its former amount for many years, until the consequences of the mixing process affect the outer envelope of the star. But the time will come when its quantity will begin to decrease, while the neutrino flux by then may already have recovered.

If one agrees that the phenomenon described periodically repeats in the life of the Sun, and since life on Earth, as is well known, depends on the amount of light, should we not look into the past for any indications that such or similar phenomena have already occurred?

It turns out that we can. Every 250 million years glacial periods set in on the surface of our planet. There are various hypotheses concerning the causes that produce them. True, when attempting to link the Great Glaciations with cycles of mixing, specialists encounter certain difficulties. But these are due primarily to the ambiguity of the "Kelvin–Helmholtz time", which we have already discussed, although there are grounds for considering these difficulties to be temporary. For the time being, however, the "mixing" hypothesis is far from universally accepted, and the problems associated with it remain a subject of debate.

While theorists continue to argue, the developing science, based on new technology, keeps supplying them with more and more facts. Observing solar flares, the crew of the "space laboratory" *Skylab* discovered a curious phe-

nomenon. It turned out that one solar flare can trigger another in a distant region of the solar surface. During a flare, a structure resembling the mushroom cloud of a nuclear explosion is formed. During one observation session, the astronauts unexpectedly saw a huge "bubble" in the solar corona. Most likely, it arose as the result of a powerful flare on the other side of the Sun, invisible from Earth.[8]

While photographing prominences, the *Skylab* astronauts and Soviet cosmonauts aboard *Salyut-4* discovered much that was new and, as yet, unexplained in the activity of our star. However, for the time being we must state that there is no direct experimental confirmation that a thermonuclear fire is raging in its interior. And yet all theories are built precisely on this assumption. How, then, should one relate to them? Exactly in this way: accepting nothing on faith. Science and faith are incompatible concepts. Though here the author begins to exploit the recipes of "Parkinson's laws", which state that "any assertion becomes truth after 1,227 repetitions". Why exactly after 1,227? Try checking it yourself...

[8] The "solar neutrino problem" was resolved around 2001–2002. Experiments such as Super-Kamiokande and, decisively, the Sudbury Neutrino Observatory demonstrated that neutrinos change flavour during their journey from the Sun to Earth. The chlorine detector of R. Davis was sensitive primarily to electron neutrinos and therefore registered only part of the total neutrino flux. When all neutrino flavours are measured, the observed flux agrees with predictions of the standard solar model. The deficit was thus not caused by mixing in the solar core but by neutrino oscillations — a phenomenon that implies neutrinos possess a small but non-zero mass. – DM

Stars in Assortment

In commerce, assortment refers to a collection of different types and varieties of goods. We are, of course, not going to trade in stars. But in our days of admission competitions for universities of commerce, such terms are especially popular. And we, for our part, are striving for clarity and an engaging presentation.

So, for comparing stars with one another, we have a single standard — the Sun. The Sun is an ordinary star. The Sun is the yardstick of stars. But before beginning the work of comparison, it would be useful to make a few clarifications. They concern, first of all, the brightness of the Sun and of stars. Here is what these quantities look like, for example, for our star and for a number of well-known stars of the northern sky:

Sun	$26^m.8$
Sirius	$1^m.43$
Vega	$+0^m.04$
Polaris	$+2^m.01$

(The figures given may differ slightly depending on the reference source used.) Here the letter *m*, as we have already said, denotes the *stellar magnitude*. An interval of one stellar magnitude corresponds to a difference in brightness of two objects by a factor of 2.512. This quantity is connected with the psycho-physiological *Weber–Fechner law*. The law states that if a stimulus changes in a geometric progression, the corresponding sensation changes in an arithmetic progression. In our case, the stimulus is precisely the brightness of a star.

Using this relation, it is easy to calculate that Polaris appears about six times fainter than Vega, Vega about four times fainter than Sirius, and so on. However, the apparent brightness of stars depends not only on their intrinsic luminosity but also on their distance. Therefore, in order to compare stars with one another by luminous power, they

must first be placed at the *same standard distance*. This distance is chosen to be ten parsecs, or 32.6 light years. The stellar magnitude reduced to this distance is called the *absolute magnitude* and is denoted by the letter *M*.

Now, following all the rules, let us move the selected four stars to the required distance and see what happens.

Good heavens! How the picture has changed! Polaris has come out in first place, shining far brighter than Sirius. Vega has also overtaken it. And the Sun? Where is our Sun? It is almost imperceptible from such a distance. To finally convince the reader of the relativity of what he sees in the sky, let us give one more example. In the constellation Orion there is the star Rigel; by observed brightness it occupies seventh place. But if we compare its true luminosity with that of the Sun, it turns out that Rigel shines with roughly twenty-three thousand Suns.

In diameter, our Sun is also a very average little star. There are larger ones, even very much larger. Such luminaries as VV Cephei, S Doradus and Epsilon Aurigae have diameters thousands of times greater than that of the Sun. Can you imagine a star whose diameter is equal to the span of the entire Solar System, bounded by the orbit of Pluto? At the same time, the mass of such a body exceeds the mass of our Sun by only a few tens of times; otherwise the star would be unstable.

Thus, any supergiant is largely an appearance. In order not to be excessively massive, it has a density that could quite compete with the high vacuum we achieve in elec-

tronic devices by pumping air out of them with expensive pumps.

There are also dwarf stars with diameters of only 15-20 kilometres, yet with masses, again, not very different from that of the Sun. Just think what their density must be like! Later, when the discussion turns to superdense bodies, we shall give some staggering figures...

Stars also differ very substantially in colour. Only to an inattentive eye do they all seem the same. Astronomers have classified all existing shades of stellar colour into 13 grades and carefully monitor their changes. Why is this so

important? Because colour changes in accordance with the surface temperature of a star. Of all the stars observed to date, the coldest is Chi in the constellation of Cygnus. Its colour is dark red, and its temperature is about 1600 degrees on the Kelvin scale. The hottest, on the other hand, turn out to be the cores of planetary nebulae; judging by their bluish-white colour, their temperature reaches up to 100,000 degrees.

But the most important characteristic of both temperature and the physico-chemical state of stars is their *absorption spectra*. The appearance of a stellar spectrum depends on many factors. These include differences in the physical properties of stellar atmospheres due to varying temperatures and pressures, differences in chemical composition, as well as the influence of the star's magnetic and electric fields, its rate of rotation, and many other factors. It is, of course, very important to understand what depends on what, how, and to what extent, and to see all the key characteristics of a star, as it were, at a glance. Stellar spectra provide scientists with invaluable assistance in this task.

At first it seemed that the boundless stellar ocean could not be classified at all in any humanly comprehensible way. But gradually it became clear that most stars can be grouped into a relatively small number of classes. At present, the so-called Harvard spectral classification is accepted. It contains ten classes, designated by Latin letters: *O, B, A, F, G, K, M* (*R, N, S*).

Students, in order to remember the sequence of spectral classes, invented a mnemonic phrase that works unfailingly: "Oh Be A Fine Girl Kiss Me Right Now Sweetie." Years may pass, one may forget how one spectral class differs from another, but whenever one sees the above sequence of letters, the magical phrase flashes up in the memory like fiery writing at Belshazzar's feast. True, there are also three additional classes of cool stars, *N*, *R*, and *S*, but either imagination failed when it came to them, or they appeared too rarely in examinations to deserve a mnemonic.

Soon, however, even ten classes proved insufficient. Each had to be subdivided into ten further subclasses. This produced a long spectral staircase of a hundred steps. Not all of them are filled evenly. Some are empty, while others are crowded, like a bus at rush hour. The hottest stars are grouped into class *O*. In the subsequent classes the temperature decreases.

At the beginning of the present century, two astronomers — Ejnar Hertzsprung in Denmark and H. Russell, whom we have already mentioned — independently constructed some curious relationships. On their diagrams they plotted spectral classes along the horizontal axis and luminosities, or absolute stellar magnitudes, along the vertical axis. One might have expected the entire field of the diagram to be evenly sown with points representing stars. In reality, it turned out quite differently. The overwhelming majority of stars arranged themselves in a long tail along the diagonal from the upper left corner of the diagram to the lower right. This diagonal was called the main sequence, and

somewhere near its middle our Sun is lost among the rest.

First of all, the supergiants and bright giants took their places on the diagram. On the left-hand side of the main sequence the hot blue stars gathered. Following them, as temperature decreases to the right and downward, came the white stars, then the yellow dwarfs, below them the red stars, and finally the very faint red dwarfs occupied the lower corner of the diagram.

The results of this work caused something close to jubilation in the astronomical world. And no wonder: at that time it was believed that the main source of a star's energy was its gravitational contraction. The diagram seemed to confirm this hypothesis. As it contracted, each star supposedly passed through all stages of evolution: from a protostar to a gloomy crimson-red supergiant; then, as heating continued, its colour became yellow and the star acquired the name of a yellow giant; after that it became bluish-white, dazzlingly bright and hot. From this moment on, the energy of contraction was no longer sufficient for heating, and the star, passing into the category of yellow dwarfs, began gradually to cool, successively becoming a yellow dwarf, a red dwarf, and finally a black dwarf. At this point the life path of the star came to an end.

It was a very elegant hypothesis, and the "H–R" diagram, as specialists began to call it after the names of its creators, represented this path with great clarity. While heating up, the star moved across the upper part of the diagram from right to left until it reached the beginning of the diagonal.

Then, in the process of cooling, it began to slide down along the main sequence. Everything found an explanation here, even the slight spread in stellar masses. Indeed, if the same star passed through all stages of development, it is hardly surprising that the masses of supergiants differ only slightly from those of dwarfs — unlike their volumes or their densities.

However, any hypothesis is good only until it is stated aloud. It soon became clear that there exist many stars that do not fit onto the main sequence at all. The "H–R" diagram broke up into a number of other sequences. And stellar evolution itself turned out to be far more complex than a calm contraction and a smooth slide along the main sequence from heat to cold. Stars sitting very close to one another on the diagonal, contrary to expectations, showed no related features whatsoever. There were both old, well-deserved veterans of the sky and young luminaries that had formed only recently.

Then A. Eddington, filled with the best of intentions, decided to calculate, at least approximately, the mass–luminosity relationship. He arrived at the unexpected conclusion that dwarfs could, in principle, be hotter than giants.

In short, with each passing year new and new inconsistencies in the hypothesis of "sliding evolution" disturbed astronomers' peace of mind. In the end, it had to be abandoned. But the "H–R" diagram itself had been constructed from observational data, and therefore it remained. More than that, it continues to play an extremely important role

in astrophysics, having become richer in content and... alas, more complex. The reader will see for himself how its ghost will stand behind many of the arguments that await him in the subsequent sections of our book. No, in science, as in a model household, nothing disappears without a trace. You may believe that.

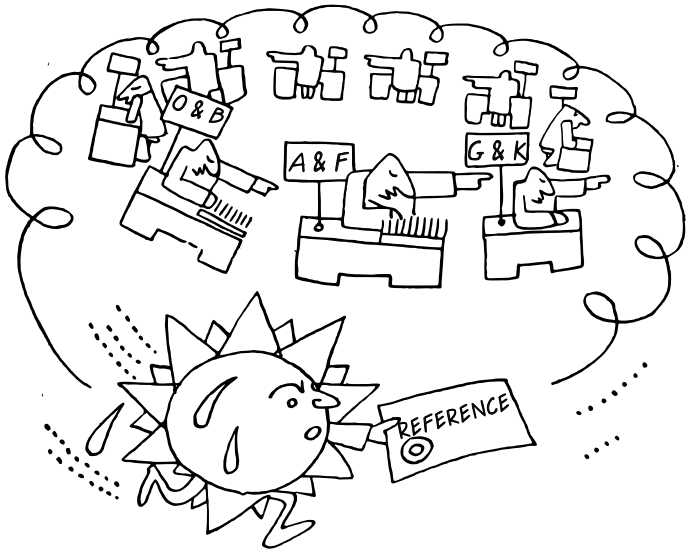
The Classical Direction of Stellar Cosmogony

In the middle of the twentieth century, specialists in stellar astronomy developed more or less reliable methods for estimating the ages of individual star clusters. A new life then began for the H–R diagram as well. Astronomers started to construct it not for all stars of, say, the Galaxy at once, but for individual clusters whose stars are of the same age. This yielded a great deal of interesting information.

By our time, astronomers have divided the entire stellar multitude belonging to the Galaxy into five main types of stellar population.

The extreme population of the first type unites the hottest stars of spectral classes *O* and *B*, as well as very young galactic clusters and associations. This also includes such building material as cosmic dust and interstellar neutral hydrogen. The next population group of the same first type includes ordinary stars of spectral classes *A* and *F*, red supergiants, and galactic clusters. Finally, the last, third group of the first-type population brings together old main-sequence stars and giants of spectral classes *G* and

K.



The population of the second type is divided into two groups. The first unites white dwarfs, as well as many types of variable stars. The second consists of globular clusters of venerable age and subdwarfs.

From the very form of the classification presented, one can already guess the scheme of stellar evolution adhered to by its authors. They clearly proceed from the assumption that all young clusters and associations coexist with large masses of building material: dust and gas. These astronomers are supporters of the classical hypotheses

which assert the formation of stars "from gas-dust complexes by condensation of dispersed matter". These hypotheses are developed in sufficient detail and differ only in the forces and in the mechanisms of action of those forces to which their authors give preference.

When speaking of the classical direction of stellar cosmogony, it is important to note that the entire process of the birth of a new luminary can be divided into two stages. The first is contraction and the transition from a gas-dust cloud to a protostar. The second is the switching on, in its interior, of thermonuclear sources of energy. But first of all it is necessary to resolve the question: why should a cloud consisting of dispersed particles of dust and gas suddenly pass into an unstable state and begin to contract?

The study of the conditions of stability of celestial bodies was once undertaken by the already well-known to us J. Jeans. He was a major theoretical physicist who was interested, in particular, in problems of radiation and the kinetic theory of gases. And it may be stated with confidence that it was precisely his successes in physics that laid the foundation for his later astronomical work.

From the conditions of existence of a rarefied gaseous nebula in the interstellar medium, it is not difficult to conclude that there are three possibilities. The first is to remain in an unchanged state while maintaining equilibrium. The second is to disperse into space. And the third is to begin to contract. Everything depends on which is greater: the intrinsic (thermal) motion of the molecules, which creates

internal pressure and tends to drive the nebula apart and disperse it, or the total gravitational attraction of the entire mass of matter.

J. Jeans, using his knowledge of gas dynamics, succeeded in deriving a mathematical criterion for the instability of such nebulae. The requirements turned out to be rather stringent. For a gaseous nebula in interstellar space to begin to contract, its mass, at a given density, must be approximately a thousand times greater than that of the Sun. Only then do the forces of gravitation exceed the gas pressure. The reader is entitled to object: stars with such masses do not exist. How many times have we said that even the most massive ones can be only slightly heavier than the Sun. But perhaps the cloud, while contracting, accumulates material at once for an entire association of stars?

Let us try to imagine how this occurs. A gigantic gas–dust complex initially contracts as a single whole. As the density increases, the criterion of instability begins to be satisfied for its individual parts as well. Then the original nebula fragments. After that, each part continues to contract separately and quite independently forms its own protostar.

Now let us select one of the condensations, close in mass to the one from which the Sun could once have formed, and follow its further evolution. Many theorists have addressed such a problem, and a whole series of its stages has been calculated in detail.

First of all, what does the chosen part of the contracting dust nebula represent? Its mass must be close to the solar mass. Therefore, at normal density it will have a radius of the order of a few tenths of a parsec. Mathematically this can be written as follows:

$$1 \text{ parsec} = 3.26 \text{ light years} = 3.083 \cdot 10^{13} \text{ kilometres},$$

and consequently one tenth of a parsec is equal to

$$3,083,000,000,000 \text{ kilometres}.$$

For the further contraction of the nebula, it is necessary that the pressure of gravitation, and to some extent the pressure of the surrounding gas, should continue to exceed its own internal pressure caused by the thermal motion of the particles. Then, after some time, the nebula will reach a critical density and pass into the next category — a protostar. The temperature of the gas should, in principle, increase in this process, but theorists maintain that it remains approximately constant because of strong cooling by the interstellar medium.

This is a very unfortunate circumstance, because a dark, cold, contracting cloud almost gives no sign of its existence in the depths of the Universe. During this period, the most intense radiation may be the infrared emission of the molecular hydrogen line. However, precisely this radiation, as ill luck would have it, does not reach observers on Earth, being absorbed by the Earth's atmosphere. One will have to wait for the construction of an astronomical

observatory on the Moon. Or else look for some other confirmation of the supposed early phases of contraction.

For example, several years ago radio astronomers discovered a puzzling radiation with a wavelength of 18.3 centimetres. Where does it come to the Earth from? What produces it? The point is that, having detected radio waves of any frequency from space, researchers eventually identify their sources. But here, no matter how hard they tried or how long they searched, they found nothing.

In complete despair, one particularly emotional radio astronomer suggested calling this radiation "mysterium". That did not help the matter. Then, quite suddenly, the Soviet astrophysicist I. Shklovsky, well known for his ability to generate the most extraordinary hypotheses, suggested that this was precisely the radiation in the line of the diatomic hydroxyl molecule (*OH*) emitted by contracting protostars. An interesting assumption. How successfully these "ownerless radio waves" have been assigned a source this time will be shown by the future. If this idea is confirmed, it will have to be acknowledged as a brilliant one.

Thus, the protostar is ready. Let us agree to consider that the initial stage of contraction of the gas–dust cloud has come to an end.

After passing through the state of critical density, the contraction process accelerates. After some time it proceeds at the speed of a freely falling body. Dust and gas race one another towards the centre of the condensation. And the distance to it is not small. Remember, we spoke

about the radius of the cloud...

Once again, the mathematicians take the floor. They have calculated that a protostar with the mass of the Sun needs approximately 200,000 years to concentrate into a celestial body of the required "stellar" density. During such intense contraction, a great deal of gravitational energy is released. At the expense of this energy, the dust and gas are heated, and the contracting protostar emits more and more electromagnetic radiation, though for the time being still entirely in the invisible infrared range.

Gradually, in the centre of the protostar, the dust begins to melt. Gas molecules break up into atoms. The atoms become ionised. The substance of the protostar passes into the state of plasma. And as soon as the released gravitational energy becomes sufficient to heat and turn the entire protostar into a plasma sphere, the violent rush of matter towards the centre ceases. One or two short outbursts occur, with a brightness a thousand times that of the Sun, and the protostar darkens again. At this stage, according to the theory of the Japanese physicist C. Hayashi, the protostar "boils" violently, like a pot of cosmic soup, heating its interior. And only when the temperature at the centre reaches something like eight million degrees do thermonuclear reactions "switch on". From this moment, as specialists say, the protostar "settles" onto the main sequence and begins the life of a normal star.

After the protostar has turned into a star, its life proceeds more briskly. The processes occurring in the interi-

ors of stars are complex and depend, of course, on many factors, but above all they depend on mass. For us, matters are simpler: we have confined ourselves to considering an ordinary star, a star of the solar type. This is simpler and more interesting because the fate of the Sun is surely far more important and troubling to us than the fate, say, of some Dabi or "Killer's Fortune", as Beta in the constellation of Capricorn was once called, located at a distance of almost two hundred and fifty light years from us.

With the onset of thermonuclear reactions in a star, the "burning" of hydrogen in proton reactions begins. During this phase, one may assume that the radius of the luminary and its luminosity remain constant for a sufficiently long time. This is a great blessing. During this period, life arose near one of the celestial bodies known to us, namely the Sun, and even achieved a certain degree of success in its development. And humanity still has time ahead for prosperity. According to modern science, our Universe has existed for at least 10 billion years. Over this span, even the oldest stars with masses smaller than that of the Sun have not yet "burned out" all the hydrogen in their interiors. But in the end this will, unfortunately, happen. By that distant time, the temperature in the interior of the Sun, according to calculations by E. Öpik, will rise to 400 million degrees. The type of reactions in its core will change, and our luminary may flare up. Although it may also not flare up.

The further course of evolution is of less interest to us. After the reserves of "fuel" are exhausted, thermonuclear

processes will cease, the star will begin to contract again, and it will do so until it turns into an iron white dwarf. The white dwarf will slowly cool, passing successively through the stages of a red dwarf, an infrared dwarf, and finally a black dwarf. Then the complete end will come. That is all.

Of course, in the picture presented of the formation of a star from diffuse matter, not everything proceeds smoothly. For example, according to observational data, there is very little hydrogen in the Galaxy: only about 2 per cent of the total mass. Yet theory holds that stars originated precisely from this ubiquitous gas. With such a meagre amount of building material in the Galaxy, all star formation should long ago have come to an end. Meanwhile, the same observations indicate that our system contains many young and very hot blue giants and supergiants. At the same time, it must be admitted that nowhere, in no corner of the Galaxy, have astronomers been able to detect a single protostar. And if such objects are formed from gas, it would be entirely reasonable to expect them among the stellar youth in associations ...

Alas, everything that has been discovered so far in this respect has turned out to be wishful thinking taken for reality. Nor does the calm nature of gas concentration into a protostar agree with the observed explosions accompanied by powerful ejections of matter, which astronomers have detected in the nuclei of galaxies.

Finally, a major shortcoming of the hypothesis considered — a shortcoming acknowledged even by all its sup-

porters — is that, even having satisfactorily explained some of the existing facts, it has so far failed to predict a single new discovery. And in recent years there have been many such discoveries. With a hypothesis that claims to rise to the rank of a theory, such embarrassments should not occur ...[9]

In the post-war year of 1946, not far from Yerevan, on the slopes of Mount Aragats, construction of the Byurakan Astrophysical Observatory began. Under its domes there gathered a group of talented and enthusiastic young people, led by V. Ambartsumian. There, continuing his studies of hot giant stars of the early spectral classes *O* and *B*, as well as variable dwarf stars of the *T* Tauri type from the constellation Taurus, V. Ambartsumian noticed that young stars are not arranged chaotically at all, but show a certain tendency to cluster. The Byurakan astronomers called these new groupings *O*-associations and *T*-associations.

But here was what was strange. The associations occupied such a large volume of space that the forces of mutual gravitation between their members should have been very weak. At the same time, the stars' own velocities of motion turned out to be so large that only a few hundreds of thousands or a few million years would be sufficient for them to leave such a collective altogether.

And now let us try, following V. Ambartsumian, to draw some conclusions. Does it not seem to you that the facts presented indicate that such unions are formations of recent origin and, on a galactic timescale, very short-lived?

[9] Subsequent research has substantially revised this picture. Stellar evolution calculations in the 1970s–1980s established that Sun-like stars end as carbon–oxygen white dwarfs, not iron ones; no black dwarfs can yet exist because the Universe (13.8 billion years old, determined precisely by 2013) is too young. Extensive surveys of interstellar hydrogen (from the 21-cm line studies onward) have shown it to be the dominant baryonic component of the Galaxy. Direct evidence of protostars emerged in the 1980s through infrared observations by IRAS (1983) and later with the Hubble Space Telescope (from 1990), while ALMA (operational 2011) and the James Webb Space Telescope (from 2022) have imaged protoplanetary discs and jets in detail. Modern stellar evolution theory is now quantitatively predictive and well tested across a wide range of stellar masses. – DM

And does the fact that these associations consist of young, very hot stars, often double and multiple systems, not suggest that they were all recently born as a close group and are now striving to fly apart from their native nest, but have not yet had time to do so? And finally, since they tend to disperse, did not some force take part in their birth, imparting to them an initial velocity sufficient to overcome Newtonian forces of attraction? ...

More than one conclusion suggests itself. And each of them is literally revolutionary, because it fundamentally contradicts the established classical point of view.

First, contrary to the idea of the great antiquity of all stars, it turns out that some of them are being born even today. And second, that stars are born not singly, but in groups and entire collectives. Reporting in 1947 to the general assembly of the Academy of Sciences of the USSR on the results of these studies, V. Ambartsumian also posed the main question: from what, then, are all these young stars formed, and how does the process of collective star formation proceed?

One could, of course, have assumed the existence of large dark pre-stellar clouds of diffuse matter and tried to imagine the grand act of star birth within the framework of the classical approach. But what the young corresponding member of the Academy of Sciences of the USSR spoke about from the rostrum had nothing in common with classical ideas. He suggested that in the depths of the Universe there exist super-dense bodies that divide into parts, form-

ing stellar associations of the observed type.

In 1950, V. Ambartsumian and B. Markarian received the State Prize for the discovery of stellar associations of this type.

The hypothesis they put forward provoked an avalanche of criticism. A well-known specialist in the physics of stars and nebulae, the Moscow astronomer B. Vorontsov-Velyaminov, questioned the very existence of associations of young celestial bodies. He believed that bands of dark dust and gas in the Galaxy simply conceal from us part of the distant giant stars, leaving between them peculiar "corridors of visibility". And what we are able to see in these "corridors", the Byurakan astronomers take to be "scattered associations". B. Vorontsov-Velyaminov based his doubts on a fairly large number of errors that he had found in the preliminary results of the Byurakan astronomers. Passions ran high. Both positions acquired supporters. The time came for a major open discussion. And it took place in May 1952 in Moscow, at the *Second Conference on Problems of Cosmogony*.

The main argument of the opponents of the new viewpoint was that no astronomer had ever seen, anywhere, the super-dense bodies from which, as V. Ambartsumian believes, stars ought to form. But after all, despite the acceptance of the classical hypothesis, its supporters were also unable to describe a nebula in whose depths nascent luminaries could be seen!

Many participants in the meeting took the opportunity

to speak about the results of their research, as a result of which astronomers became acquainted with an interesting theory of star formation from diffuse matter, put forward by the Leningrad professors A. Lebedinsky and L. Gurevich. Academician V. Fesenkov spoke about studies of stellar chains discovered by him with the aid of a magnificent new telescope installed at the Alma-Ata Observatory. He also outlined a possible course for the evolution of various galactic nebulae, from which, in his opinion, stars arose.

Many specialists spoke at the meeting. In the end, the ideas defended by V. Ambartsumian prevailed. The majority of participants agreed with the existence of stellar associations. However, in the heat of the polemic, the main question for which the discussion had been organised — namely, the question of the origin of stars — was somewhat pushed aside and forgotten.

In the resolution that was adopted, the "fruitfulness" of the notion that the process of group star formation continues at the present time" was acknowledged.[10]

New Wineskins for New Wine

Even in the biblical commandments it was said that old wineskins should not be used for young wine — it will turn sour. Over the centuries, this valuable household advice has acquired a deeper meaning. Let us try to adapt it for our own purposes as well.

Do you remember how we spoke about V. Ambartsum-

[10] The existence of stellar associations is now well established. In the 1950s–1960s improved spectroscopy confirmed that *OB* associations are physically related groups of young stars. Radio observations of molecular clouds in the 1960s–1970s (especially *CO* surveys) demonstrated that stars form within cold, dense interstellar gas, not by fragmentation of hypothetical super-dense bodies as Ambartsumian proposed. Infrared observations with IRAS (1983), high-resolution imaging by the Hubble Space Telescope (from 1990), and precision astrometry from Gaia (launched 2013) have since mapped ongoing group star formation throughout the Galaxy with great accuracy.

ian's discovery of scattered stellar associations consisting of very young stars, which are striving with all their might to escape from their original company? But have you not wondered why they seek to do so? For if they are formed by the condensation of diffuse matter, then, being born as a close-knit collective, they ought inevitably to form stable systems. Why, then, should they fly apart in different directions?

New astronomical technology has enabled observers to penetrate extremely far into the depths of the universe. What was previously seen only dimly and indistinctly could now be discerned with sufficient clarity using new instruments. If earlier our Galaxy, like other galaxies, appeared to be a calm and stable formation, new methods of investigation dispelled this illusion. Violent processes are taking place in all corners of the metagalaxy. Development proceeds in steps marked by explosions and catastrophes of incredible power. New stars suddenly flare up in the sky. This term — new stars — was not invented by observational astronomers without reason.

It seems that only yesterday there was nothing remarkable in a given region of the sky, and today a bright point suddenly emerges there. A little time passes, and the "new" star reaches the luminosity of the most powerful supergiants. Then, just as suddenly, it begins to fade. At maximum, the luminosity of the star increases by hundreds of thousands of times. And this is an explosion — and what an explosion! In the short time of a "new" star's outburst — over the course of only a few days — there is released

as much energy as our Sun emits over ten, or even one hundred thousand, years.

But even more magnificent are the explosions of "supernovae". True, from a human point of view this is not such a frequent phenomenon. The last such outburst in our Galaxy was probably observed by Johannes Kepler in 1604, even before the invention of the telescope. Kepler's "supernova" was visible even in daylight, in sunlight. Its luminosity is estimated to have been billions of times greater than that of the Sun and only slightly less than the luminosity of an entire galaxy. It was a truly super-grandiose explosion. According to the statistics of the astronomer F. Zwicky, such explosions should occur in galaxies approximately once every three to four hundred years. If one compares the lifetime of a galaxy with the lifespan of a human being, such outbursts are like a galactic pulse or the beats of a galactic heart. A meaningful, though clearly anthropocentric, analogy.

But these explosions do not exhaust the grandiose cataclysms of the universe. In the nuclei of galaxies there occur as yet poorly understood explosion-like processes, accompanied by the release of colossal amounts of energy and by the ejection of matter. So might explosions be a normal phenomenon of development in the cosmos? So to speak, a leap-like transition from one qualitative state to another, in accordance with the dialectical law of development?

If this is so, then the disintegrating associations of young stars also receive a natural explanation. One only needs to

find the cosmic charge that serves as the source of the explosion that scatters them. And V. Ambartsumian puts forward a hypothesis of the formation of stellar systems from invisible super-dense concentrations of matter, which he calls "*D*-bodies". Thus a new cosmogonic hypothesis was born, fundamentally opposed to the classical approach.

The "new wineskins" were fashioned so unusually that the stunned cosmogonists at first unanimously greeted them with hostility. The supporters of V. Ambartsumian took comfort in the fact that in the entire history of science there has never been a case when a new step could be taken easily and without resistance from the orthodox. This, too, is one of the great laws that helps to preserve the accumulated wealth of knowledge. Imagine what would happen if any scientific assertion were immediately accepted by humanity on faith?

Around V. Ambartsumian there rallied an energetic collective of like-minded researchers. At the Byurakan Observatory an entire school of the new direction emerged, a school faced with complex tasks. After all, literally everyone tried to prick them with the reproach that they were attempting to explain one unknown by means of another unknown. Indeed, no one had ever seen the hypothetical super-dense 'D-bodies'. There were not even indirect confirmations of the very possibility of the existence of such formations. Doubts were expressed as to whether matter could exist at all in the required super-dense state. A difficult struggle lay ahead for the young Byurakan astrophysicists. Every word, every assertion and conclusion

had to be justified, provided with an appropriate theory, and confirmed by observations ...

The fact that no one had ever seen the formation of stars from diffuse matter by concentration either was not taken into account by the opponents. That was the customary point of view; and in order to argue against it, facts and yet more facts were required, rather than speculative reasoning about invisible, and perhaps even non-existent, super-dense bodies.[11]

Nevertheless, astronomers already had some experience of dealing with the super-dense state of matter. It was begun by Friedrich Bessel. As early as 1844, observing the motion of Sirius, he came to the conclusion that an invisible companion must necessarily be revolving around the bright giant, and a sufficiently massive one at that, since certain irregularities were observed in the motions of the bright star. However, observers found no companion near Sirius. And only 18 years later, when the optician and astronomer Alvan Clark was testing a newly polished objective on his telescope, did he see next to Sirius a tiny sparkle barely noticeable in its radiance. This was Bessel's "Sirius B", or the "Puppy", as some astronomers called it.

Although "Sirius B" was quite hot, it nevertheless emitted 10,000 times less light than Sirius itself; consequently, it had to be many times smaller in size as well. But the mass of the "Puppy" differed from the mass of the primary luminary by only a factor of two. Only one conclusion was possible — the substance of "Sirius B" had to be heavier,

[11] Powerful energy release in galactic nuclei is now understood primarily in terms of accretion onto supermassive black holes. The discovery of quasars (1963) and subsequent observations established that active galactic nuclei are not explosive "charges" in Ambartsumian's sense, but are powered by gravitational energy from matter falling into central black holes, whose existence was firmly confirmed by stellar-orbit measurements in the 1990s and by direct imaging of black hole shadows in 2019. Ambartsumian's hypothetical super-dense "D-bodies" did not find observational support. Modern star-formation theory explains stellar associations as products of gravitational collapse and fragmentation of giant molecular clouds, a framework strongly supported by radio, infrared, and space-based observations since the late twentieth century. – DM

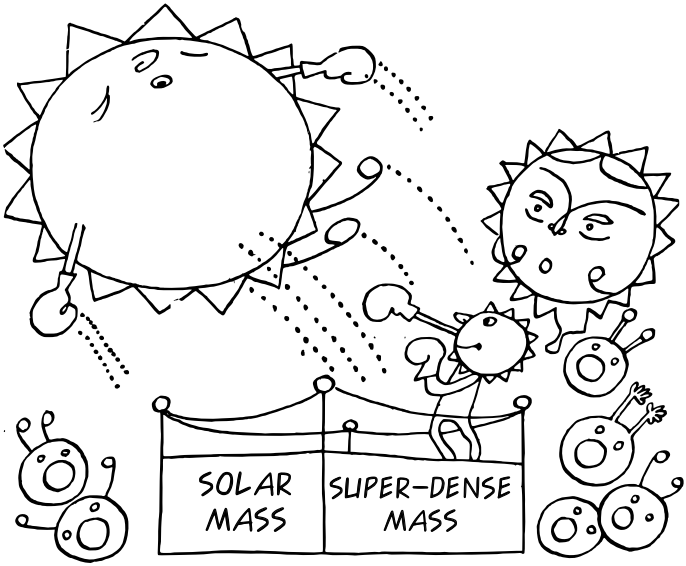
that is, denser than the stellar matter of Sirius itself. And so it proved to be. Thus, in the history of astronomy, the first white dwarf was discovered — a star composed of matter of increased density.

Time passed, and so many white dwarfs were discovered that they formed an entire special class of stars. Theoreticians developed an appropriate theory, derived the conditions under which white dwarfs could exist and remain in equilibrium, and worked out the physics of the formation of condensed matter. What will not be done on paper when observations demand it. According to all the data, the stellar matter of white dwarfs seemingly should not obey the equation of state of a gas, derived as early as 1834 by B. Clapeyron. In 1874 it was generalised by D. Mendeleev and since then has played an essential role in calculating stellar models. The equation of state of a gas can be used when gases are sufficiently rarefied. But it is completely inapplicable to the super-dense state of white dwarfs. So what could these astonishing clumps of matter consist of, and in what phase state must their substance be?

Let us try to reason it out. The surface temperature of white dwarfs reaches 10,000 degrees. Inside it is certainly higher. Therefore, they cannot be either solid or liquid. Gaseous? But the density of matter in the interiors of these stars is such that, under terrestrial conditions, a thimble filled with a similar conglomerate would weigh hundreds, or even thousands, of tonnes! Meanwhile, the density of the densest solid and liquid bodies known to humankind does not exceed twenty grams per cubic centimetre.

In 1926 the English physicist R. Fowler nevertheless derived, in theory, the conditions under which the enormous density of the matter of white dwarfs could exist. Everyone felt relieved. R. Fowler assumed that the interiors of this type of star are in a state of a "degenerate gas", in which atoms are destroyed, electrons are separated from nuclei, and the distances between the centres of atomic nuclei are several tens of times smaller than in ordinary liquids and solids. Such matter must possess completely special properties.

Let us recall some physics. Why does a gas in its ordinary state have a low density? Because its atoms move freely in space. The distances between them are greater than the sizes of the atoms themselves. In liquids and solids the picture is different. There, atoms, swollen by their electron shells, are in contact with one another. And the tighter their "packing", the higher the density. In the matter of a white dwarf the nuclei are bare, the electron shells have been torn away from them. But the distances between them are still significantly greater than the sizes of the nuclei themselves. And this is a sign of a gas. Well, not quite an ordinary gas, of course — and that is why it was called "degenerate"...



Several years later the Soviet physicists L. Landau and Ya. Frenkel independently came to the conclusion that not every star can turn into a white dwarf, but only one whose mass exceeds the solar mass by no more than 40 per cent. Subsequently, the Soviet physicist M. Bronshtein and the Indian physicist S. Chandrasekhar, working in the United States, laid the foundations of the general theory of white dwarfs.

The astrophysicist S. Kaplan in the USSR solved the problem of the most probable densities of such stars. It turned out that white dwarfs are very diverse. Their density, and accordingly their radius, depends on the assumed

chemical composition. For example, if a white dwarf consists mainly of helium, its maximum density will be "only" one thousand tonnes per cubic centimetre. Such a celestial body may have sizes comparable to those of medium-sized planets. But if the greater part of a white dwarf consists, say, of iron nuclei, its limiting density increases by about a factor of 20, and its radius becomes smaller than the radius of the Earth (of the order of a thousand kilometres).

But even these are not the limits of what is possible. Theory allowed that conditions may occur in space under which the density of contracting stars will cross beyond the limits of the densest white dwarfs. This will happen when the bare nuclei of the "degenerate gas" begin to absorb electrons, turning their protons into neutrons. Nothing prevents neutral particles from being "packed" even more compactly, right up to contact. In this process the star contracts sharply, and the density of its matter increases to hundreds of millions of tonnes per cubic centimetre.

At first, neutron stars were simply "invented" by theorists. The concept of them was born in the minds of astronomers W. Baade and F. Zwicky in 1934. Later, L. Landau and W. Hund provided a theoretical foundation for their supposed existence. R. Oppenheimer and G. Volkoff calculated the first model. It turned out that neutron stars could form as a result of supernova explosions. In this case, part of the star's gaseous shell is torn away by the force of the explosion and flies off, while the remaining matter at the end of its evolution shrinks to a density comparable with that of an atomic nucleus.

But the masses of neutron stars, just like the masses of white dwarfs, can differ from the mass of the Sun only slightly. Their radii, however, become equal to 30, or even 10 kilometres... Monstrous chimeras of the stellar world! But do they really exist? After all, one can imagine anything, even with the help of mathematics. The task of science is to limit human imagination within the framework of the laws of nature.

Until very recently, numerous attempts were made to attribute the properties of neutron stars now to one, now to another discovered celestial object. All these efforts were marked by uncertainty and ended in failure. But then, at the end of the 1960s, the astronomical world experienced a shock unlike anything before: pulsars were discovered — radio sources that change their emission within fractions of a second, operating, as it were, in a pulsed mode. Disputes about the nature of these new objects, theories of their structure, and hypotheses about their origin flared up like fireworks among specialists. And within less than three years, everyone, or almost everyone, agreed to regard pulsars as rotating neutron stars.

After fierce discussions, conducted at a fairly rapid pace, specialists agreed to consider pulsar models as certain devices resembling rotating radio searchlights. On the surface of such stars, active regions are assumed to exist that emit strictly directed radio waves. After a certain period, equal, say, to the time of rotation about their own axis, the beam of such a searchlight "brushes" past the Earth. At that moment, radio astronomers receive a pulse of radio

emission from it. But then, why should a star resemble a "searchlight" at all? Would it not be simpler, following tradition, to assume that a sphere should emit equally in all directions, and to attribute the spasmodic flashes of radio emission to pulsations, in principle analogous to processes of this kind already known?

Do you notice that we are no longer questioning the existence of these strange objects, but are already discussing quite matter-of-factly their possible structure...

There is an opinion that both models have the right to exist. Moreover, it is not excluded that for some pulsars both models may be applicable simultaneously, in combination.

Is it possible to imagine a further increase in the density of stellar matter beyond the neutron state? This problem was taken up on the theoretical level by V. Ambartsumian and G. Saakyan. They established that with a further increase in density, neutron matter must pass into a new, baryonic state. That is, crushed neutrons and protons must partially pass into the unstable state of hyperons — the heaviest of the elementary particles known at present. Hyperons are extremely unstable. Under normal conditions their lifetime amounts to billionths of a second. But we should not expect normal conditions in the depths of a compressed star. Far from it. The conditions there are such that the newly formed hyperons simply have nowhere to decay. As a result, they begin to accumulate in the centre, forming a hyperon core.

The model of such a star can be imagined as consisting of several layers. The inner part is the hyperon core, in which other heavy particles may also occur. The main mass of the star is concentrated here. Then follows the next — neutron — layer, consisting, as the reader has probably already guessed, of neutrons. It is of medium thickness, and its mass is "insignificant". And the last — outer — layer, one might even say not a layer but a very thin film, consists of "bare", stripped nuclei and electrons — a film composed of white-dwarf matter.

The gigantic internal pressure in hyperon stars is balanced by no less monstrous forces of gravitational compression. In this case, any disturbance of the star's equilibrium must lead to an explosion beside which even the explosions of "supernovae" pale.

Everything seemed to have worked out splendidly. Supporters of the new concept were ready to celebrate. It was clear that hyperon-stars were precisely the mysterious "*D*-bodies" from which entire collectives of stars are born in explosions...

Clear — but not quite. The developed theory allowed stars with masses also of the order of the solar mass to pass into the baryonic state. More massive formations had no right to pass into the superdense state. A veritable vicious circle emerged. For such masses were clearly insufficient for entire stellar collectives to be born from them.

"Black" and "White Holes" of the Universe

In March 1974, a curious notice appeared at the entrance of the P.N. Lebedev State Astronomical Institute of the USSR Academy of Sciences. At a joint seminar, a report entitled "Do 'White Holes' Explode?" was to be presented. The scientific authority of the speakers — Ya. Zeldovich, I. Novikov, and A. Starobinsky — together with the unusual nature of the topic, attracted the attention of many.

In general, cosmologists are primarily to blame for the appearance of such strange and "unscientific" terms as "black" and "white holes". Once, while developing the hypothesis of the "Big Bang", they were the first to describe the process as a result of which "everything" was formed out of "nothing". In a sense, they even competed with the Lord God. True, their "cosmological nothing" had infinite density at a point. God's "nothing", on the other hand, really was "nothing".

However, cosmologists also prefer not to dwell too much on the very moment when "nothing" turns into "something". It is a dark matter — theoretical... Their main research concerned the time when matter had already been born and had begun to fly apart in different directions, forming our universe. It is natural to assume that, as they fly apart, clumps of matter should slightly slow one another down by the forces of mutual attraction. And therefore the speed of their motion should gradually decrease.

Any line of reasoning must be confirmed by calcula-

tions. Calculations were carried out in this case as well. An unpleasant result emerged. In order to slow down the existing galaxies, the total mass of matter in the universe would have to be about ten times greater than that obtained by adding up all observable matter: galaxies, gas clouds of nebulae, and even the mass of cosmic-ray particles. Taken together, all this gives only 10 percent of the required mass. But where should the remaining 90 percent come from? This is where "black holes" came to the rescue. If they cannot be seen, then why not assign to them responsibility for the missing mass of the universe?

In general, it must be said that these objects — invented as early as 1939, theoretical, hypothetical, and anything you like except real — turned out to be a veritable treasure trove for astronomy. However, serious observers always treated them sceptically. And then suddenly... But first, what are they, in fact?

Considering the process of collapse — the unstoppable contraction of a star at the end of its evolutionary cycle, when all hydrogen fuel has been exhausted — theorists arrived at some curious conclusions. We have already said that ordinary stars with masses of the order of the Sun's mass can contract to the density of an atomic nucleus and turn into neutron condensations. This too was at first only a supposition, but then pulsars were discovered.

Investigating the process of contraction further, theorists established that stars with masses exceeding that of the Sun by five, ten times or more contract without limit,

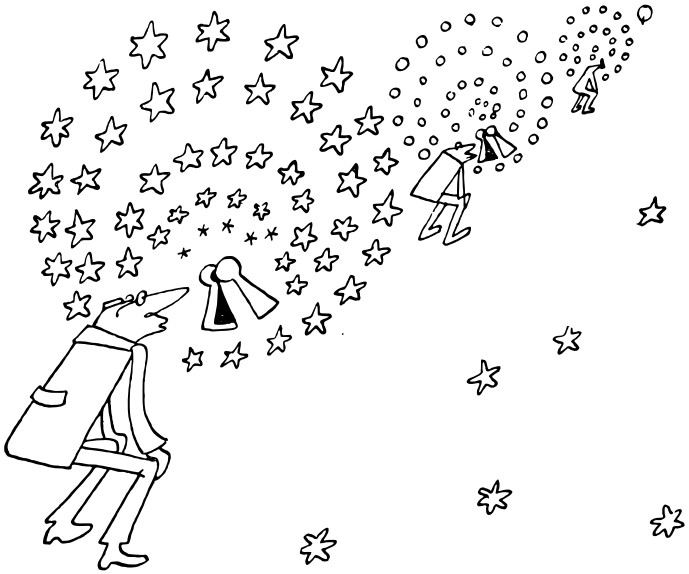
that is, they collapse, turning into a "black hole". In this case, despite a sharp reduction in radius, the mass of the star remains the same. And can you imagine how the conditions near such a gigantic sphere of matter, shrunk to a tiny volume, must change?

If the size of a body becomes smaller than the so-called gravitational radius — a quantity depending on the mass of the star and the speed of light — then for an external observer it disappears from view. To help the reader visualise this quantity more clearly, it is enough to say that for the Sun, with a photospheric radius of about 7×10^5 kilometres, the gravitational radius is only 3 kilometres.

For a collapsed object, the gradient — that is, the measure of how rapidly gravity increases at the boundary defined by this radius — becomes so great that no radiation can penetrate through it. Particles and rays, bent back by the forces of frenzied gravity, scarcely leaving the surface, immediately fall back again, carrying no information familiar to us beyond the gravitational radius. Neither photons of visible light, nor infra-, nor ultra-, nor radio-, nor X-, nor gamma rays are able to break through such a barrier. For an external observer the luminary simply seems, as it were, to disappear. And only its forlorn planets, comets, and asteroids continue to move in impenetrable darkness along their former orbits.

It disappears, yes — but only from view. In principle, it remains, and its gravitational attraction at a distance does not change. However, in regions close to a "black hole" all

processes are now described not by Newton's laws, but by the general theory of relativity. In these regions even the properties of space–time change: the geometry of space is distorted, and time slows down. What results is indeed something like a hole in space–time. A hole through which theoreticians and astrophysicists strive to peer, attempting to extract from it information about the most fundamental properties of the surrounding world.



It must be said that the hypothesis of "black holes" is equally attractive both to supporters of the old, classical cosmogony and to supporters of the new one. Some see in

them a fine example of the final stage of stellar evolution. Others firmly believe that the existence of "black holes" is the most important proof of the existence of a super-dense state of matter, and consequently of the validity of the new viewpoint on the formation of stars.

Let us imagine that the conditions of equilibrium of a lump of matter compressed to the density of a "black hole" were disturbed, and that it exploded. You may ask: why did it explode?

Who knows. We have already remarked more than once that stars are inclined to this form of expression of their character. But when "black holes" explode, they turn into their antipodes — into "white holes". And if before the explosion they could be regarded as the product of the final stage of evolution, then after the explosion this is clearly the beginning of evolution. A super-dense body gives rise to new celestial objects.

Perhaps it is precisely here that the junction of two cosmological concepts that are irreconcilable today will finally take place ...

About ten years ago, Professor I. Novikov, while considering the conditions for the emergence of quasars, proposed the following hypothesis. When the Big Bang occurred and our universe began to expand from a super-dense state, some of its parts failed to keep up with the general pace. For certain reasons, they remained for some time in their primordial state and only much later joined the overall rhythm. These individual parts, having survived

almost up to our time, are quasars, or special points of the universe, so to speak, a "scattered singularity".

A distant observer, looking at them, should most likely see in the space of the metagalaxy certain "black holes", which, after the passage of a definite period of time, suddenly explode and turn into "white holes".

One must agree that quasars and active galactic nuclei are ideally suited to play the role of "white holes". However, Novikov's original hypothesis did not take into account the quantum effects accompanying the birth of particles and therefore failed to hold together consistently. And so we come to the new report with which we began this section.

The speakers did not boast at all that they had now supposedly found and taken into account every aspect of the phenomenon. Refinements of the theory led to the conclusion that, for "white holes", two extreme states are equally possible: one unstable, and the other, on the contrary, absolutely stable. In the first state a "white hole" explodes immediately, within a hundred-thousandth of a second after its formation. In the second case it will never explode, remaining for the observer an eternal "black hole".

It is true that common sense suggests that, when extremes exist, the middle does not remain empty. A delay of the explosion for some definite period of time is also possible. But so far, according to calculations, this would require such highly improbable initial conditions that such a phenomenon should occur in the metagalaxy only exceptionally rarely. And yet quasars and active galactic nu-

clei are not few in the observable space. Which means ... Which means that the theory being developed to explain them is once again insufficient.

The conclusion is not a particularly cheerful one for the creators of the theory, but it is a conclusion. And if it is not confirmed, no great harm is done; in science it is not uncommon for a negative result to be more valuable than many positive ones.

But do these hypothetical objects actually exist? So far all reasoning has not gone beyond the limits of theoretical assumptions. Indeed, how can they be searched for if they are invisible? Well, first of all, one might try to look for certain whirlpools" of cosmic gas being drawn into a black nothingness". As it approaches a "black hole", the gas falling onto it will begin to radiate. Perhaps these will be radio waves, or perhaps *X*-rays? Detecting such radiation, while scanning the sky densely strewn with stars, is far from a simple task.

There is another path as well. Do you remember how F. Bessel, in his time, inferred the existence of an invisible companion of Sirius? And what would happen if the vassal were greater in mass than its suzerain? Then the bright Sirius would revolve around an invisible point, bound to it by the ties of gravitation. From the Earth it would seem to us that it is orbiting around empty space.

In the Universe there are many binary stars. It cannot be ruled out that among them there may be such pairs in which one of the components is a "black hole". In that

case the normal companion of the object of interest to us should continuously lose its matter, which will flow towards the invisible companion, swirl around it, and form a disc. Friction between the gas layers will disrupt the disc, and it will become a source of *X*-ray radiation. In addition, in the gas vortex, as it approaches the gravitational radius, magnetic fields grow stronger. Charged particles of the gas plasma are accelerated under these conditions and, consequently, begin to emit variable electromagnetic waves. Theoreticians have calculated the period of these oscillations. It turned out to lie within the range of ten-thousandths of a second. Such "black holes" were called fluctuars. Now only a very little remains — to find them in the sky!

The situation would not differ at all from the one in which we intended to search for gas "whirlpools", were it not for the second star of the pair.

X-rays from the gas disc intensely bombard the nearby normal star, unevenly heating one of its sides. A kind of "hot spot" appears on the surface of the star. And such a phenomenon can be detected even from the Earth, using optical methods.

In recent years, very many specialists have been engaged in the theory of *X*-ray sources and in the radiation processes of systems containing "black holes". A major contribution was made by researchers of the P. Sternberg State Astronomical Institute. There is an opinion that astronomers have almost certainly found at least one "black

hole". In the constellation of Cygnus a suspicious pair is observed, consisting of a normal star — a supergiant — and a component invisible in optical light, with a mass of the order of ten solar masses. Intense *X*-ray radiation, the close proximity of the companions, and the fact that the radiation spectrum in many respects corresponds to what was theoretically predicted, all inspire hunters of "black holes".

As yet there is no one-hundred-per-cent guarantee that the invisible object has been caught. However, judging by how rapidly the flux of *X*-rays changes, its source must be spinning very briskly about its axis. And this means that it is of exceptionally small size. And with such smallness, during each burst — which lasts no more than a thousandth of a second — more energy is released into the surrounding space than in the explosion of a billion hydrogen bombs. It is precisely this comparison that Ya. Zeldovich, I. Novikov, and R. Sunyaev use when speaking about studies of these new objects.

Today the attention of specialists of different profiles in different countries is focused on the search for "black holes". Astrophysicists hope, with their help, to penetrate more deeply into the interiors of stars and to test the validity of existing laws and theories. Theoretical physicists expect from "black holes" confirmation or refutation of their assumptions about the properties of space–time in the vicinity of these phenomena. Cosmogenists place great hopes on the new objects, counting on refining the mechanism of the origin of stars and resolving many disputes of

a fundamental nature. New celestial objects are physical laboratories with unique conditions and possibilities. It is impossible to model them on Earth. Therefore it is necessary, at any cost, to find reliable ways of obtaining from them the information that they so generously scatter into space. That is why observations of *X*-ray sources have occupied, and continue to occupy, such an important place in the programmes of work of orbital stations...[12]

So how, after all, are stars born?

The birth, evolution, and internal structure of stars are questions inextricably linked with one another. These are, perhaps, the most extreme frontiers of present-day astrophysics, the most interesting and topical problems of stellar science. The reader may already have formed a certain impression of the complexity of research into the world of stars. For, besides a multitude of painstaking observations, every model required and still requires such an inconceivable amount of computation that it is beyond the power not only of a single person, but even of an entire collective of a single scientific institution. Only the era of high-speed electronic computing machines has opened new horizons for solving this problem.

Stellar evolution consists of a chain of very complex processes. Scientists of even the first half of our century were aware of this. Giant gaseous atomic reactors — that is how stars may be called for the sake of popularisation — turned out to be not only extremely diverse, but also prone

[12] The object described is Cygnus *X*-1, identified as a strong *X*-ray source in the 1960s and widely accepted as a black hole candidate by the early 1970s. Its black hole nature is now regarded as firmly established: precise mass measurements in the 1990s and 2000s showed the compact object to exceed the maximum possible mass of a neutron star. Since then, many stellar-mass black holes have been discovered in *X*-ray binaries, and supermassive black holes have been confirmed at the centres of galaxies. Decisive evidence includes stellar orbit measurements around the Galactic centre black hole (1990s–2000s; Nobel Prize 2020) and direct imaging of black hole shadows by the Event Horizon Telescope (2019 for *M87**, 2022 for Sagittarius *A**). Black holes are now central, well-confirmed elements of astrophysics rather than hypothetical objects. – DM

to increasing complexity with age. We have already said that problems of stellar evolution are being developed by specialists in many countries. Moreover, in recent years a tendency has emerged towards cooperation in collectives not merely of individual astronomers and astrophysicists within a single scientific institution, but of the institutions themselves in international unions. And since such unification is always associated with the choice of the most important directions of research, it may be worth describing the organisation of one of them in more detail.

In 1972 the Academy of Sciences of the USSR signed bilateral agreements on joint research on the problem "Physics and Evolution of Stars" with the academies of sciences of Hungary and India.

In 1973, in Warsaw, an Agreement on multilateral cooperation was signed between the academies of sciences of the socialist countries (the People's Republic of Bulgaria, the Hungarian People's Republic, the German Democratic Republic, the Polish People's Republic, the Socialist Republic of Romania, the USSR, and the Czechoslovak Socialist Republic) on the same problem. Several months later, representatives of the friendly academies gathered in the city of Tsiolkovsky — Kaluga. A founding meeting took place. The participants outlined paths for joint research in six of the most topical directions of stellar science, dividing these directions according to interests among the academies of sciences.

The very first research direction is called *Early Stages*

of "Stellar Evolution". It includes calculations of the hydrodynamic contraction of a cloud of interstellar matter, the formation of a protostar, the ignition of nuclear energy sources, and, finally, calculations of the earliest stages of evolution taking into account its interaction with the surrounding "medium".

The task of coordinating research in this field was assumed by the Czechoslovak Academy of Sciences. Moreover, at the final stage of the work it is envisaged to compare the results of the calculations obtained with the results of special observations.

The Polish Academy of Sciences took upon itself the supervision of the second topic — "Study of the Late Stages of Stellar Evolution". By late stages, astrophysicists mean those periods of stellar life when various energy sources are already operating in the depths of the gaseous sphere and the star, complicating its structure, expands, turning into a red giant. This also includes the calculation of models of a "pre-supernova" and a "supernova" star, when they suddenly increase their luminosity by billions of times and shed their gaseous shell, losing part of their mass.

The Hungarian Academy of Sciences is the coordinator of the theme devoted in general to the property of nonstationarity in the life of stars. Observations have shown that among the stellar population there exist objects that change their parameters both regularly and sporadically: brightness, colour, spectrum. Meanwhile, a satisfactory explanation of the causes of these changes does not yet

exist. That is why non-stationarity was singled out by the meeting as a separate problem.

A very interesting type of celestial objects are stars possessing anomalously strong magnetic fields — the so-called "magnetic stars". Today the time has already come to unite disparate observational results into a single whole and to develop models of the mechanisms for the generation of magnetic fields. It is also desirable to determine definitively the degree of influence of magnetic fields on the structure and evolution of stars. This important and topical theme is coordinated by the Academy of Sciences of the GDR.

The next theme of this broad front of research is the evolution of close stellar systems. After all, binary stars make up almost half of all massive stars in our Galaxy. Calculations and observations of recent years have shown that in the course of evolution, matter flowing from the more massive, expanding star may either surround both components with a single luminous shell, or form into jets, or even pass entirely into the composition of the second component of the pair. But why? The participants of the meeting came to the conclusion that the time has come, first, to systematise the obtained data on binary stars, then to carry out calculations of the evolution of close binary systems, and, finally, to compare the results of the calculations with observations. The coordinator of this theme is the Academy of Sciences of the Socialist Republic of Romania.

We have already spoken more than once about the importance of studying groups of stars. Despite the differences in their properties, stars belonging to associations and clusters apparently share one very important common characteristic — approximately the same age. This means that their comprehensive study will make it possible to test many hypotheses and theoretical calculations and, consequently, will bring greater certainty to our understanding of the processes of star formation. This theme and direction are coordinated by the Academy of Sciences of Bulgaria.

Since many of the indicated directions are being developed in the Soviet Union, the coordination of all directions has been entrusted to the Academy of Sciences of the USSR. Such a unification of efforts promises very interesting results in solving many important problems of modern astrophysics and cosmogony.

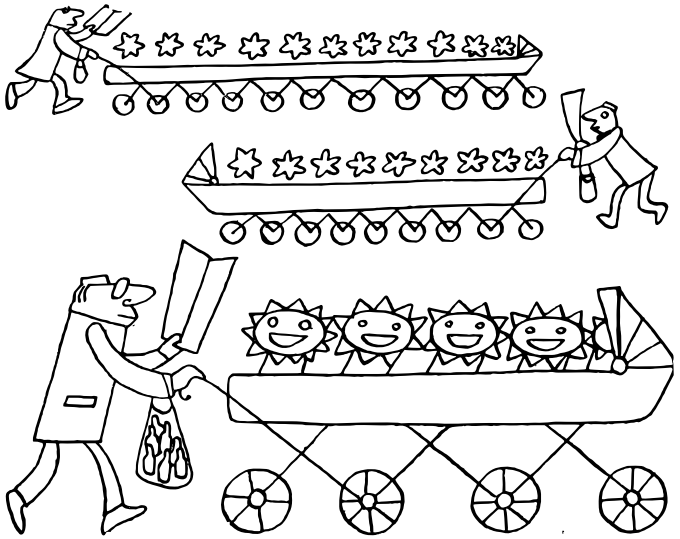
The reader will probably sense that the section devoted to stellar cosmogony is drawing to a close. It is time to draw some conclusions, and we are faced not merely with a rich set of hypotheses, but even with two opposing concepts. The first, still the more widespread, regards the process of creation as the condensation of rarefied matter. The second holds that the formation of stars occurs as a result of an explosion-like disintegration of superdense bodies. Which of these two viewpoints should be preferred?

There is hardly a worse situation than one in which it is necessary to exercise independent judgement, especially

when this concerns a theory of the origin of stars. Both concepts have arguments "for" and arguments "against". Perhaps it will be easier if these "for" and "against" positions are compared. Let us try, in conclusion, to arrange some of them one after another in the form of "objections–assertions" along the main lines of the debate. For example

1. **Stars are being born even in our own time.**
   Previously, the classical concept asserted that all the stars of the Galaxy arose simultaneously.
   The new concept rejected this assertion from the outset. According to present-day views, stars continue to be formed even now.
2. **Stars are born in groups.**
   Supporters of the new concept, who advanced this assertion, base it on observations. Among young stars united in associations there are many unstable multiple systems.
   Moreover, the associations themselves are continuously expanding and are therefore very fragile unions. This gives grounds for supposing that star formation occurs in groups, within common centres.
   Specialists who adhere to the classical concept raise objections. They argue that no stellar associations supposedly uniting young hot supergiants actually exist. In the groupings cited as examples, alongside young stars one also observes a considerable number of old, cool stars.
   At present, too little evidence has been accumulated to assert the existence of associations of young stars.

Moreover, even if one accepts the dispersal of stars belonging to such a collective, the cause of this phenomenon could quite plausibly be, for example, a supernova explosion. Such an explosion, having expelled a significant mass of matter from the cluster, could have brought the entire system into an unstable state.



In summary, it may be said that, despite the existing disagreements, the idea of the group birth of stars is prevailing. Today even supporters of the classical direction in cosmogony are developing mechanisms for the formation not of single stars, but of entire stellar collectives at once.

3. **What is the initial material in the formation of stars?**
   The classical concept: stars are formed as a result of the gravitational condensation of diffuse matter. It is not excluded that electromagnetic forces play a significant role in the processes of formation.
   The new concept: in 1952, Academician V. Ambartsumian wrote: "Every close group of stars must arise in an association from a single body of pre-stellar nature. These hypothetical bodies may be called protostars." What protostars are, modern science does not know in concrete terms. It is assumed that these are super-dense bodies of sufficiently large mass, consisting of matter in a form unknown to us. Possibly, this is its pre-stellar stage.
4. **If one agrees that stars are not born singly, then protostars must also possess masses many times greater than, for example, the mass of the Sun. Is this possible?**
   Supporters of the classical concept answer this question evasively. They say the following: theory does not yet provide conclusions about the conditions of stability for such masses. Observational results also do not yet make it possible to say that anyone has seen these super-dense formations. Therefore ...
   And here is what supporters of the new concept say: "In nature there may exist super-dense static stellar configurations with masses of the order of galactic and higher." This is written by the well-known theoretician from the Byurakan Observatory, G. Saakyan.

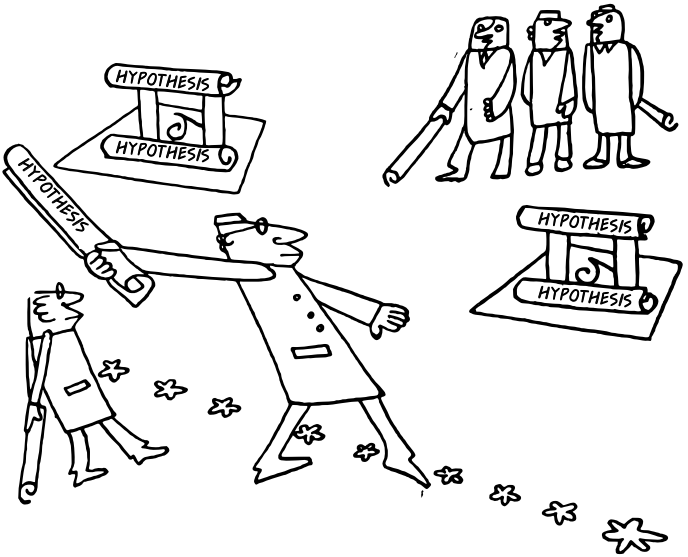
In addition, in 1963 observers discovered quasars, and today they are engaged in the search for "black holes". Why should one not assume that these are precisely such super-dense formations?
Yes, it appears that on this question the supporters of the two concepts diverge decisively.

5. **Which mechanism of star formation is preferred?**
The classical mechanism: star formation occurs through the gravitational contraction of a large nebula. At first it contracts as a whole. Then, when the Jeans instability criterion begins to be satisfied for its individual parts, the nebula breaks up into separate condensations that give rise to protostars.
Supporters of the new concept believe that the main process of star formation at the present stage of the Galaxy's development is their emergence as a result of an explosion from a single super-dense body.
An explosion in the Universe in general is a regular, step-like transition of accumulated quantitative changes into a new qualitative state.

Of course, this is only the principal outline of the dialogue between representatives of different points of view. In reality, it contains far more content and persuasive force. Here it is presented merely as an example, in order to say in conclusion that, for the time being, the choice of one or another concept remains a matter of taste.

A major merit of the new approach of V. Ambartsumian's school to cosmogonic phenomena may be considered the assignment of a central role to non-stationary objects

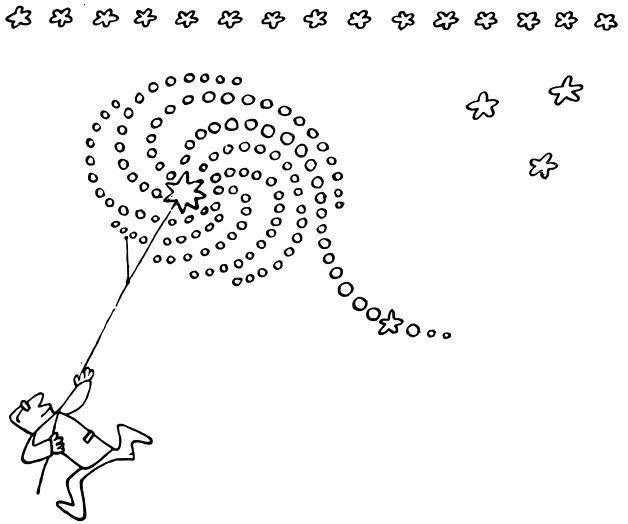
in the development of the Universe and to explosive processes. The new point of view is gradually strengthening, and the number of its supporters is also growing. This is understandable. "The calm picture of a slowly changing world, in which the states of all objects are almost stationary," wrote V. Ambartsumian, "fully harmonised with the orderly mechanical ideas about the Universe developed on the basis of celestial mechanics and the then just emerging astrophysics ..." That was the time of the calm nineteenth century.



But it was followed by the twentieth century, a century of devastating cataclysms in society, science, and technol-

ogy. Calm and stability were replaced by a tense, nervous life, full of major and minor upheavals. They affected all aspects of social life and did not leave a single person untouched. The worldview also had to change. The new hypothesis of the Soviet cosmogonic school seems as if it was itself born out of the new rhythm of our life. Whether it will turn out to be more correct than the existing classical concept is a dispute that only time can resolve. Well then, the stars are in no hurry ...

8 Cosmogony of Galaxies



Nebulae or Galaxies

This is the youngest branch of the science concerned with the origin and development of celestial bodies and their systems. It is young because only in our twentieth century did new, powerful astronomical technology make it possible to confirm the assumption of the existence of other galaxies — enormous stellar systems like our own Galaxy — containing hundreds of billions of stars, usually united into various groupings. As recently as 100 years ago, many astronomers considered our Galaxy to be the only system in the universe. Beyond it — emptiness. Like a huge swarm of bees, the Galaxy hangs in empty Newtonian space without end and without edge. In shape, this swarm resembles a millstone or a lentil.

In addition to individual stars and star clusters, the Galaxy included a fairly large number of "shaggy objects", as small misty patches in the sky of unknown nature and incomprehensible composition were called in the previous century. It is true that W. Herschel managed to discern stars in some of them, but most remained blurred spots, indistinguishable in any instrument. They were therefore called "nebulae". They did not greatly interest specialists. Disputes were conducted mainly over a particular question arising from cosmogonic disagreements: is the well-observed nebula in the constellation Andromeda a gaseous embryo of a future planetary system belonging to the Galaxy, as P. Laplace had claimed, or is it an independent stellar system, so distant from us that it cannot

be resolved into stars by any of the instruments then available?

At the end of the nineteenth century, astronomers acquired a new powerful instrument of research — the spectral method. The light of stars, passed through the prism of a spectroscope, produced an almost continuous spectrum crossed by dark absorption lines. Gas heated until it glows, under the same conditions, produces a line spectrum.

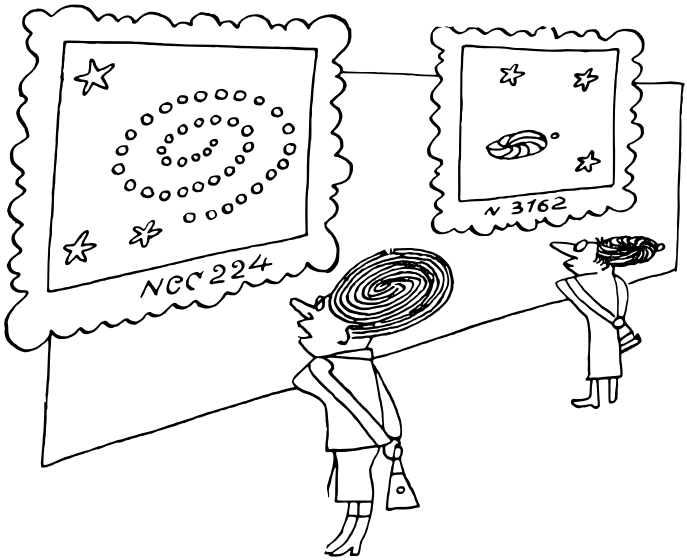
The spectrum of the Andromeda nebula, obtained in 1899, turned out to be continuous. It might seem that the question could now be considered closed, that the stellar composition of the nebula had been proven. Not at all. The dispute was only beginning to flare up in earnest. Why not suppose, argued the supporters of the nebular nature of the object, that what we see is a cloud of cold gas which does not shine by itself but merely reflects the light of stars? That, they said, is why its spectrum is continuous...

But, objected their opponents, where then are the stars whose light the nebula is reflecting?

There were no stars.

Only in 1917 did the astronomers R. Curtis and G. Ritchey notice several bright points in the Andromeda nebula. Like tiny sparks, they flared up and then disappeared after a few days. The observers concluded that these could be new stars, visible at moments of maximum brightness. From the observed brightness they calculated the distance to them. It appeared monstrously large — about fifteen times

greater than the diameter of the entire Galaxy. This was an important result, because it showed that the misty patch of spiral structure located in the constellation Andromeda and bearing the catalogue designation NGC–224 is an extragalactic object.



Thus arose the "Great Debate" — are all nebulae in fact extragalactic objects, or do they belong to the population of our own Galaxy? These disagreements already touched upon such fundamental questions about the structure of the universe that they could not leave any astronomer indifferent. In 1920, a formal debate was even organised in Washington between two representatives of opposing

viewpoints. H. Shapley defended the position of the "long distance scale", while his opponent H. Curtis argued in favour of short distances. However, only further research could resolve the contradictions.

And so, in 1923, the young astronomer E. Hubble, having gained the opportunity to work with what was at that time the largest telescope, at the Mount Wilson Observatory, directed its two-and-a-half-metre mirror towards the Andromeda nebula. At last! On the photographic plate, stars were clearly visible along the edges of the nebula. By the end of the same year, E. Hubble also found a variable star there, similar in its properties to a Cepheid. Cepheids were precisely the objects used by terrestrial observers to determine stellar distances, and the "Great Debate" came to an end. The Andromeda nebula lay beyond the boundaries of our Galaxy and clearly had a stellar composition.

You may ask: but what about the other nebulae? In the others, at that time, no stars had yet been detected. One could, of course, assume that all objects of the same type — for example, those with spiral structure — have the same composition and are stellar systems. But there also existed nebulae of other kinds... In short, there was still much work to be done.

Remember that in the chapter devoted to planetary cosmogony we devoted quite a lot of attention to the work of the brilliant English astronomer J. Jeans. At that time, the discussion concerned the origin of the Solar System. In fact, however, the work of this astronomer also covered

stars and nebulae. His studies date from 1916–1919, when the stellar nature of NGC–224 had not yet been proven and all nebulae were considered to consist of gas.

At the beginning, according to J. Jeans, there existed space filled with a uniformly distributed rarefied gas, a kind of primordial chaos with a density of about

$$10^{-30}\ \text{g/cm}^3 \text{ or } 10^{-15}\ \text{g/km}^3.$$

Well, if the reader manages to imagine such an extremely tenuous mist, one can only envy their imagination.

There is little point in discussing the reasons why primary condensations and inhomogeneities began to arise in this "cosmic jelly". There may be many reasons, and they are studied by a branch of physics known as gas dynamics. Investigating the theory of gravitational contraction and rotation of such primary gas clouds, J. Jeans came to the conclusion that at an early stage nebulae of regular spherical shape are formed.

Then, continuing to contract and therefore increasing their rate of rotation, such a nebula becomes flattened. Gradually, matter begins to flow out from the edges of the elliptical disc, forming spiral turns. J. Jeans saw the cause of the formation of spiral arms in tidal effects produced by the gravitational fields of neighbouring nebulae. The increased density of matter in the spiral arms, in turn, served as the basis for the formation of stars within them.

In 1925, when J. Jeans first set out his theory of the formation of spiral structure in nebulae, the American as-

tronomer E. Hubble compiled the first classification of nebulae. First of all, he divided them into three large groups: irregular, elliptical, and spiral.

Leaving aside the first type of nebulae, he arranged all the others into a certain sequence of forms. The beginning of this sequence consisted precisely of spherical nebulae. E. Hubble assigned them the index E_0, meaning "elliptical — zero flattening". Then, in accordance with the ratio of the major and minor semi-axes of the ellipsoids, followed the classes $E_1, E_2, \ldots, E_7$. More strongly flattened nebulae E. Hubble was unable to find.

After that came two branches of spiral nebulae. One branch united normal spirals, the other — barred spirals.

J. Jeans was very pleased with the Hubble classification. It poured water on his mill, fully corresponding to the evolutionary sequence of nebulae that he had outlined. And E. Hubble himself, despite trying not to link the classification with evolution, was, deep down, convinced that J. Jeans was right. In general, everything seemed to be going very well. The Hubble classification and the Jeans hypothesis became classical and entered all textbooks. It is true that the Jeans hypothesis did not cope very successfully with the formation of spiral structures in galaxies. But the first half of the hypothesis — the transformation of spherical gas clouds into elliptical ones — raised almost no doubts. And suddenly ... This "suddenly" refers to the time when the Second World War was drawing to a close: it was the year 1944. But it all began earlier.

In the early 1930s the astronomer W. Baade, whom we have already mentioned, arrived in the United States from Germany, from the Hamburg Observatory. Whether he came permanently or temporarily is now difficult to say, given the passage of time. Only one thing is known: from 1931 onward he was a diligent member of the staff of the Mount Wilson Observatory, which was quite reasonable, since in those years his kind fatherland had little time for stars. The Americans, for their part, allowed the German to use the 2.5-metre reflector, despite the fact that W. Baade retained German citizenship. How reasonable this was is hard to judge. In any case, had he become an American citizen by 1941, perhaps that very "suddenly", for the sake of which we have taken an interest in the far-from-astronomical details of this high-class specialist's life, might never have occurred.

On 24 June 1941 the President of the United States, F. Roosevelt, issued a statement in support of the Soviet Union in its war against fascist Germany. A subject of the "Thousand-Year Reich", W. Baade was declared by the local authorities an "ally of the enemy" and was forbidden to leave the observatory grounds. Then came Pearl Harbor and the introduction of compulsory blackout regulations in Los Angeles and the surrounding cities. Taking advantage of the especially dark nights, the astronomer W. Baade photographed selected celestial objects. And then the day came when, examining photographic plates bearing images of elliptical nebulae, W. Baade discovered that they, too, consist of stars. There was no doubt about it. He was

even taken aback before he could feel joy at the discovery. For it meant that the theory of J. Jeans should be consigned to the archive. Remember, all the reasoning of the English astronomer had been based on the assumption that elliptical nebulae were certainly gaseous formations, still facing a long evolutionary path before the first stars could appear within them. Now the foundation beneath the entire elegant and beautiful theoretical edifice of J. Jeans crumbled away. Cosmogenists had to begin everything anew.

Normal galaxies ought to be born in this way ...

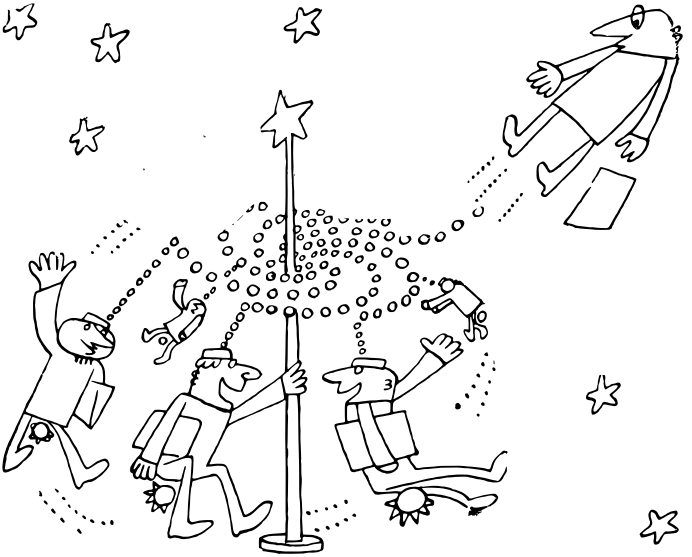
The 1940s of our century were marked by many curious discoveries in stellar astronomy, discoveries that played a decisive role in the cosmology of galaxies. Despite the collapse of the theory and the cracks that appeared in the foundations of the cosmological views of Jeans–Hubble, the basic idea of the origin of galaxies through the condensation of gaseous matter remained unshaken and admitted no doubt. Disputes concerned questions of a more particular nature, and above all the direction of evolution.

Investigating the stellar composition of the Andromeda galaxy, W. Baade discovered that the stars freely distributed in its spiral arms differ substantially from the tightly packed stars of the nucleus. Approximately the same picture was observed in other stellar systems, including our own. This allowed W. Baade to divide the stellar "population" of our

Galaxy into two types. To the first type he assigned stars from the spiral arms. This also included members of open clusters and, in general, stars gravitating towards the equatorial plane of our system. They received the name of stars of the flat component. To the second type belonged the stars of the nucleus, of dense globular clusters, as well as certain types of stars surrounding the centre of the Galaxy in the manner of a halo. They were called stars of the spherical component. The stars of elliptical galaxies were also assigned to the second type of population.

Later, the work of other specialists complicated this classification by subdividing the populations of both classes into further subclasses. But the principle proposed by W. Baade has survived to this day.

Three years after the studies described above, the Soviet astronomers B. Kukarkin and P. Parenago demonstrated that the stars of the spherical component are older than the stars of the flat component. Having thus learned to distinguish stars by age, it became possible to attempt a similar division of galaxies into young and old formations. And here the unexpected began. It turned out that spiral galaxies are populated by younger stars than elliptical ones. Hence, they themselves ought to be younger. But the classical Hubble evolutionary sequence asserted the opposite: namely, that elliptical systems, degenerating, transform into spiral ones. In short, the new discoveries demanded an immediate revision of the old rules.



The situation was further complicated after a report by the well-known American astronomer H. Shapley. According to his data, the largest number of young, bright supergiants is found in galaxies of irregular shape — precisely those that had not even been included in Hubble's classification. To this was added a new work by B. Kukarkin, which drew the attention of scientists to clusters of galaxies containing stellar systems of the most diverse forms.

From all this, new conclusions suggested themselves. First, that no transition from one type of galaxy to another exists, and that stellar systems were formed already in the forms in which we observe them. And second, that

perhaps, even among galaxies, it is appropriate to suppose a mechanism of collective birth, analogous to that which takes place in stellar cosmology.

As was to be expected, the new observational results also provoked a fresh surge of interest and creativity among theorists. In the chapter devoted to planetary cosmogony we have already become acquainted with the hypothesis of K. Weizsäcker concerning the turbulent mechanism of the formation of the Solar System. However, the hypothesis of the German specialist embraced all sections of cosmogony, including the origin of galaxies. In his view, in the period preceding the appearance of stars the Universe represented a chaos of "diffuse gaseous matter in a state of strong turbulence". This meant that gigantic vortices raged everywhere in the primordial nebula.

How can one fail here to agree with the assertion that everything new is merely well-forgotten old? Recall R. Descartes. In the hypothesis of the French philosopher the Universe, too, was initially filled with vortices. True, they were not called by the attractive term "turbulence", nor was there such convincing mathematics. R. Descartes did not know the details of the description of subsequent stages of development, but the idea ... agree that the idea was virtually identical.

Just as once in the Universe of R. Descartes, so in the Universe of K. Weizsäcker, under the action of vortical motions there arose the first condensations, the first clouds of dust and gas of irregular shape. The clouds rotated about

their axes, flattened in the course of rotation, and turned into spiral galaxies. Note carefully — into spiral, not elliptical ones, as required by the canons of Jeans–Hubble. From the centre, diffuse matter, under the action of centrifugal forces, moved towards the periphery and became denser. In the spiral arms inhomogeneities arose. This continued until, in the depths of these inhomogeneities, the first stars flared up. By their radiation they heated the surrounding gas, and the process of star formation was first slowed down and then ceased altogether. Spiral galaxies gradually began to lose their arms, turning into stable elliptical systems.

It is interesting that, in the opinion of K. Weizsäcker, the rate of such an evolution corresponded to the sizes of galaxies: small ones passed through their path more rapidly, large ones more slowly. This was required by the turbulent character of the development of gaseous masses, and it was precisely here that all the inconsistencies and contradictions of his hypothesis began.

Clusters of galaxies consisting of systems differing both in shape and in size did not fit into the outlined scheme. Moreover, according to the hypothesis of K. Weizsäcker, all the stars in each galaxy ought to have formed at approximately the same time. But then it was unclear why observers see so many young and hot stars in "old spiral galaxies". No, cosmogenists could not so simply turn upside down the stable evolutionary scheme of Jeans–Hubble ...

The next important theoretical step was the theory developed by the Swedish astronomer Bertil Lindblad — President of the International Astronomical Union in 1948-1952. Investigating stellar systems having the form of a rotating ellipsoid, he derived strict mathematical conditions under which zones of insufficient mechanical stability arise in the equatorial regions of ellipsoids. Stars located in such a zone can break away from their circular orbits and scatter, forming spiral arms. In this process the instability only intensifies. With time, the greater part not only of the stars but also of the gaseous matter of the ellipsoid (or, one may say, of the galactic nucleus) passes into the spiral arms.

The splendid mathematical theory of B. Lindblad greatly enriched science. The methods developed by the Swedish astronomer are applied in the dynamics of stellar systems to this day. Yet specialists could not agree with his evolutionary scheme of galaxies either.

First of all, if stars pass into the spiral arms from the nucleus, then, evidently, they ought to be in the spirals either of the same age as those remaining in the nucleus or older. However, all observers unanimously declared that the spiral arms are populated by young and hot supergiants and giants, whereas in the nucleus old stars of the second population type predominate — that is, sub-dwarfs, *RR* Lyrae-type stars, and old luminaries united in globular clusters.

Furthermore, according to the theory of B. Lindblad, spiral galaxies ought to rotate with their spirals leading, that is,

unwinding. Observations, however, indicated the opposite here as well. In general, his conclusions, detached from the practical results of observation, were of too abstract a character. An excessive preoccupation with the mathematical aspect of the problem at the expense of observational data is not a shortcoming of B. Lindblad alone. As if in opposition to the words of F. Bacon, which we took as the epigraph to this book, the head of the Cambridge school of cosmogenists, F. Hoyle, declared:

> "The difficulty lies not in inventing a scheme of the process, but in choosing between the various possibilities that present themselves."

A very interesting hypothesis was developed in the early 1950s by two Leningrad scientists — A. Lebedinsky and L. Gurevich. They held that the formation of galaxies from rarefied diffuse matter does not occur simultaneously. Some were only just beginning to form when others already existed. The process of formation, in their view, proceeded as follows: first there arose a gigantic condensation of rarefied matter — a *protogalaxy*; then such a protogalaxy began to contract approximately as this process had already been described by J. Jeans: a gigantic rotating cloud flattened, acquired an energetically favourable spiral structure; stars formed in the spiral branches, after which the galaxy again thickened, turning into an elliptical one.

The chief shortcoming of the theory just described was, first of all, that no one had ever observed protogalaxies. Moreover, the two authors never explained the process by which the spiral structure of a contracting cloud arises. Yet

this was perhaps one of the most important problems of cosmogony in those years.

In 1958 another Leningrad astronomer, T. Agekian, undertook to solve this problem. According to his results, elliptical galaxies may evolve from more flattened forms towards spherical ones. Once again a contradiction with Jeans–Hubble. At the same time, elliptical systems in no case pass into spiral ones. Spiral galaxies, for their part, become more flattened with time, yet they also have no right to transform into elliptical systems.

The conclusion is thus reinforced that the classes of galaxies depend not on the evolutionary stage at which they are found, but on the conditions under which their formation began.

The mechanism proposed by T. Agekian found wide application in the study of the evolution of galactic nuclei, as well as stellar systems of smaller scale.

The American researcher F. Zwicky suggested that spiral galaxies nevertheless arise from condensations of other types. Let us imagine, he said, the approach of two or several nebulae. It is clear that as a result of gravitational, and perhaps some other, interaction, protrusions will appear in the clouds, stretching both towards the encountered neighbour and correspondingly in the opposite direction. But the nebulae that have met will soon move apart. The long arms, lagging in their rotation behind the nuclei, will then wind up into spirals.

The proposed mechanism is plausible enough. Yet it is unlikely to withstand a test of probability. Encounters in interstellar space may be too rare, while spiral galaxies are too numerous.

All the hypotheses listed above, in which gravitational forces play the principal role, were created and flourished mainly before the beginning of the 1960s. Gradually, however, astrophysicists began to devote increasing attention to magnetic fields. And in the classical direction of galactic cosmogony new motifs began to sound.

Magnetic Fields In Galaxies

In 1945 the English astronomer F. Hoyle, already familiar to us, published his hypothesis according to which the diffuse primordial matter of the Galaxy was concentrated under the influence of a magnetic field into two arms extending from the central region and arranged along magnetic field lines. Rotation twisted them into a spiral, and since then the magnetic field of the Galaxy has retained the rarefied gaseous matter within the spiral arms. But its strength is insufficient to hold the stars. For this reason the stars continually leave the arms, filling the space between them.

If F. Hoyle's hypothesis is accepted, then young stars should be located in the spirals, and old ones in the interarm regions. It is interesting to note that observations fully confirmed this conclusion. It is, however, rather difficult to determine priority precisely: which came first — the theory

that was confirmed by observations, or the observational results for which a theory was subsequently formulated.

F. Hoyle's colleagues, the astronomers H. Bondi and T. Gold, proposed their own version of the formation of spiral arms from interstellar gas captured by the Galaxy during its wanderings through intergalactic space. But these are particulars. The main task was first to prove that a magnetic field exists in the Galaxy at all. For until then no one had succeeded either in observing it or, still less, in measuring it. What if it did not exist at all? Yet, as the saying goes, those who seek always find something.

At first two astronomers — one in the Soviet Union, V. Dombrovsky, and the other in the United States, W. Hiltner — discovered a curious phenomenon: the light from stars, travelling along the line of sight, that is, along the line star–observer's eye, turns out to be polarised. And the greater the amount of dark matter along the path of the light ray, the higher the degree of its polarisation. "Why should this be?" astrophysicists reasoned. "It is one thing for dark matter to absorb the rays. It ought simply to weaken them, not to polarise them..."

The only explanation to which specialists arrived was the assumption that dark matter[13] consists of a collection of elongated, needle-like dust particles. Under the action of a magnetic field these particles become similarly oriented in space and ... polarise the light.

Well, it is not an especially convincing explanation, to say the least. Yet try to find a better one. In any case, there

[13] The term "dark matter" here means interstellar obscuring matter (dust and gas), not what we now call cosmological dark matter. – DM

was indirect confirmation of the existence of magnetic fields in the Galaxy.

Later, when powerful explosions were discovered in the nuclei of galaxies, and in our own Galaxy sources of radio emission and streams of heavy elementary particles were found, it became possible to regard the existence of a magnetic field in the Galaxy and in other galaxies as conclusively established. Without its restraining forces, all these particles would long ago have dispersed into intergalactic space.

In 1964, at the *XII General Assembly of the International Astronomical Union*, Professor Jan Oort (The Netherlands) delivered a very interesting report entitled "The Structure and Evolution of the Galactic System". Touching upon the behaviour of charged particles, the speaker remarked: "Their velocity (cosmic rays are meant – AT) is so great that, if they were not retained by magnetic fields, they would leave the system within a time of the order of 100 thousand years." J. Oort speaks of the significance of magnetic fields in the "life" of a stellar system as of a self-evident fact.

True, he immediately laments that the role played by these fields in the dynamics of interstellar gas remains completely unclear. The Dutch professor even maintains that "at the present moment we seem to know more about what cannot be explained than about what positive contribution they (magnetic fields — AT) make to the understanding of the complex phenomena observed in this gas."

Relying on the non-uniformity of the observed distribu-

tion of matter density in the observable region, J. Oort considers that galaxies "were formed from inhomogeneities in the expanding universe." These inhomogeneities could expand only up to a certain stage — until they accumulated sufficient mass and began to contract under the action of their own gravity. Thereafter, the type of galaxy that formed depended on the magnitude of the angular momentum of the protogalaxy.

With rapid rotation, centrifugal forces did not allow the diffuse matter to condense densely. A considerable amount of it remained in the outer regions, and the galaxy turned out to be spiral.

With slow rotation of the initial inhomogeneity, the galaxy became elliptical. It was precisely in this latter type of formation that there were possibilities for all the matter to pass into stars. This was an important conclusion, because, as B. Kukarkin discovered, only spiral galaxies are rich in diffuse matter; in elliptical galaxies it is not observed at all. Elliptical galaxies consist solely of stars. J. Oort considers that the primary stars in a galaxy were formed at first in a completely chaotic manner. Under the influence of the initial inhomogeneities of the gravitational field they were repeatedly mixed and only gradually, under the action of mutual gravitational attraction, gathered towards the centre.

This hypothesis agreed well with the observations. Indeed, the spherical component of the stellar population consists of old stars. Part of the remaining gas, which did

not concentrate into stars at an early stage, most likely formed a thin disc in the plane of the Galaxy, with a denser concentration towards the centre. Here, too, stars began to form — first in the nucleus, where the gas was denser, and then in the periphery.

Gradually the process of star formation slowed down. Of course, it cannot be ruled out that it may still continue even now. But its rate must be extremely low.

Again, the proposed mechanism is confirmed by observational results. In the nucleus of the Galaxy the stars are older, whereas the very young ones, formed during the second period of evolution, were distributed in the spiral arms.

It now becomes clear why all the stars born from the gas that collected into a flat disc correspond to the population of only the first type observed in the Galaxy.

From then on, no one doubted that galaxies possess magnetic fields. Cosmologists also came to appreciate the role of magnetic forces in evolutionary processes. If only one could understand where these magnetic fields originated.

Here it is necessary to return to F. Hoyle's hypothesis. At one time he expressed the general idea that the magnetic field of a galaxy is the overall intergalactic magnetic field, amplified by the compression of diffuse matter during its condensation, and then twisted by the rotation of the forming galaxies. This idea was taken up and developed by

the Moscow astrophysicist N. Kardashev and the English radio astronomer J. Piddington. According to their view, stellar systems are born already possessing a ready-made magnetic field.

Then the Soviet physicist S. Pikelner, using the apparatus of cosmic electrodynamics, attempted to draw a picture of the formation of spiral arms. The result was not without merit. Moreover, through the outlines of this preliminary sketch there began to emerge a new magneto-gravitational hypothesis. It contained bold proposals and many interesting conclusions, but no more than that: quantitatively the ends did not meet. In order to sustain the spiral arms, the magnetic fields would have had to be far stronger than those that actually exist in galaxies.

> "We seem to be beginning to understand something of the main features of the distribution and motion of the stars, and we even feel that we possess a rough outline of how our stellar system might have arisen and evolved. Moreover, we can understand why the interstellar gas is concentrated into a thin layer and why this layer rotates. But at that point our understanding of the behaviour of the gaseous component of the Galaxy comes to an end.
>
> We do not understand either the origin of its spiral structure or even how this structure can be maintained.
>
> We do not know the causes of the motion of the gas away from the nucleus in the central regions, nor do we know why the gas density is so low near 4 kpc from the centre.
>
> We do not know why, in the rapidly rotating nuclear

> disc, the matter appears to be in a state different from that which we encounter elsewhere.
>
> We also do not know why this disc has an exceptionally sharp outer boundary.
>
> We do not know what the galactic corona consists of, nor how one should interpret the remarkable systematic motions of the gas outside the galactic plane... We seem still to be standing on the threshold of a world in which we see marvellous phenomena but cannot understand them."[14]

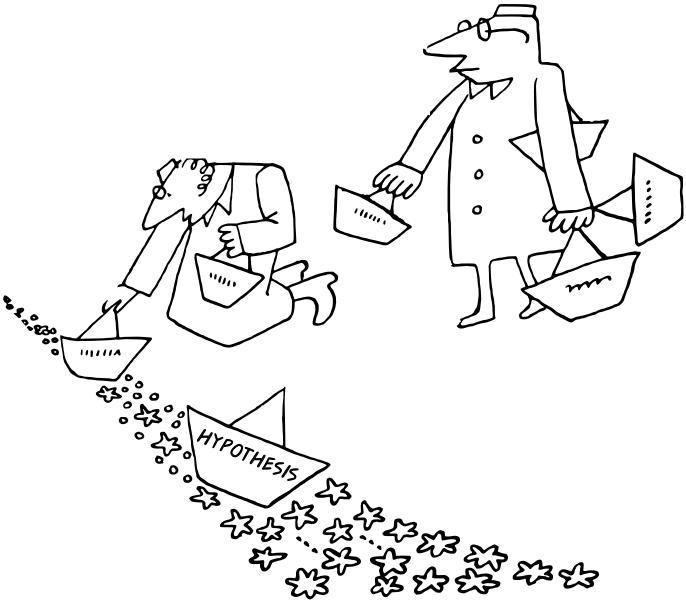
With these words Professor J. Oort concluded not only his report but also the scientific views of the 1960s on the role of magnetic fields in the evolution of our Galaxy and, consequently, of other stellar archipelagos. Indeed, one has only to look at a photograph of some galaxy to see at once that the spiral arms encircle the nucleus no more than one and a half turns. But why not more? According to calculations, they ought to wind up far more tightly. Moreover, in gamma galaxies, according to B. Vorontsov-Velyaminov, there exist both winding and unwinding branches.

The directions of the magnetic lines of force, according to observations by different astronomers, also fail to coincide. Some indicate them in one direction, others in the opposite direction. And each, naturally, considers himself right. Yet at present one cannot state with certainty that the spiral branches are indeed located solely along the lines of force of the Galactic magnetic field.

Strictly speaking, the magnetic field in a nebula ought, in principle, to hinder its condensation and, consequently,

[14] Many of the questions listed here have since received substantial clarification. The spiral structure of the Milky Way is interpreted mainly through density wave theory (1960s onward) combined with transient dynamical processes. Gas motions near the Galactic centre are now understood to be influenced by the central supermassive black hole, Sagittarius A*, whose mass was precisely measured in the 1990s–2000s (Nobel Prize 2020). The low-density region near 4 kpc is associated with resonances and bar dynamics in the Galactic disc. The Galactic corona is now known to consist largely of hot, diffuse ionised gas (detected in *X*-rays from the 1970s and mapped in detail in later missions). Large-scale surveys — especially in radio, infrared, *X*-ray astronomy, and Gaia astrometry (from 2013) — have transformed the Milky Way from a poorly understood system into one whose structure and kinematics are mapped with high precision, though important dynamical questions remain open. – DM

stars ought not to form within it.[15]



The author realises that such a conclusion resembles an old anecdote. When visitors came to the ambassador of one of the great powers, the embassy secretary met them and listed sixty-four reasons why the ambassador could not receive anyone that day.

"In addition," the secretary added with a sigh, "the ambassador cannot receive you today because he died yesterday..."

[15] Galactic magnetic fields are now well established (typical strengths of a few microgauss), but they are not considered the primary cause of spiral structure. Spiral arms are largely explained by spiral density wave theory (C.C. Lin and F. Shu, 1960s), in which the arms are long-lived density enhancements rather than material features tied to magnetic field lines. Modern observations, including radio surveys and Gaia astrometry (from 2013), support this view, though transient and dynamically evolving spiral patterns also occur. – DM

Has the magnetic hypothesis ultimately died? Perhaps not. Yet it can no longer claim today the role of the "only correct" one.

In recent years, a new wave hypothesis has been actively developed by scientists. The reader has surely noticed that when the sea is rough, all floating debris is driven towards the shore, while the water itself remains in place. Perhaps something similar occurs in the Galaxy: certain gravitational waves capture the slower stars belonging to the first population type and compress them. In any case, the first solutions of the equations linking the density of matter in the Galaxy, the gravitational potential, and the velocities of stars as a function of their distance from the centre yielded the equation of a spiral. Does this not suggest that a spiral density wave disturbance may be a stable formation capable of persisting during the rotation of the Galaxy? Then perhaps the wave hypothesis may help to resolve the "cursed question" of the spiral arms.

However, the wave hypothesis is still only gaining momentum. It is too early today to speak of its results. Yet the very fact that it has attracted the attention of specialists from many different countries suggests its possible fruitfulness.

How Are "Abnormal" Galaxies Born?

While debates revolved around the old Hubble classification concerning the birth and evolution of normal galaxies,

the situation was more or less peaceful. However, in the post-war years, radio astronomers began to seize one position after another in this ancient science. The introduction of new observational methods and new technology led quite literally to an avalanche of discoveries. According to existing estimates, the use of radio telescopes produced in astronomy no smaller a qualitative leap than in 1609, when G. Galileo first turned his telescope towards the sky.

The 1950s marked the beginning of the second revolution in astronomy. It was during this period that radio astronomers discovered regions in the sky from which veritable waterfalls of electromagnetic energy poured down to the Earth, invisible in ordinary optical telescopes. Gradually, radio sources were identified with optical objects. Some of them turned out to be the remnants of once-flaring "supernova" stars in our Galaxy. Today they appear as shreds of gaseous clouds, within which streams of charged particles rush about at sub-light speeds and are slowed in the snares of magnetic fields. Their "radio cries" constitute a significant portion of galactic radio emission.

Another group of radio sources lay clearly beyond the boundaries of the Galaxy and were identified with strange objects that came to be called "peculiar", that is, anomalous, galaxies. The power of their radio emission exceeded their emission in the optical range and significantly surpassed the radio emission of normal galaxies.

In short, clearly "abnormal" galaxies had been discovered, and they soon insistently demanded their place within

the general scheme of cosmogonic evolution.

We shall still have occasion to encounter many of them, and therefore it is worth at least listing some of the noteworthy discoveries that played a definite role in shaping cosmogonic views in recent decades. A complete register of the discoveries of the 1950s–1970s would, of course, look far more impressive.

After radio galaxies had been identified with optical objects located beyond the boundaries of our Galaxy, a wave of hunting for extragalactic novelties swept across the world. Thus the Mexican astronomer G. Haro discovered a class of "blue galaxies" with an enhanced ultraviolet portion of the spectrum. The new objects proved to be densely populated with young, hot giant stars. Then, in Moscow, at the *Sixth Conference on Problems of Cosmogony*, B. Vorontsov-Velyaminov reported on "interacting galaxies". These were mainly multiple systems connected by bridges, furnished with tails, or immersed in clouds of "luminous nebula". Later the Americans K. Lindsay and A. Sandage published a class of "exploding galaxies". And then came the era of quasars — the greatest astronomical riddle, unresolved to this day.

The stream of discoveries continued to grow. The astronomer F. Zwicky discovered "compact galaxies", regarded by many specialists as very young formations of matter in the Universe. T. Matthews, W. Morgan, and M. Schmidt introduced a class of "N-galaxies", so named because of their bright, small nucleus, clearly visible within a reddish

envelope. Almost simultaneously, A. Sandage reported the discovery of quasags — dense extragalactic formations, so called by abbreviation of the lengthy term "quasi-stellar galaxies".

In 1967 the Byurakan astronomer B. Markarian published a list of celestial objects that later became known as "Markarian galaxies".

Meanwhile, rockets, artificial Earth satellites, and automatic interplanetary stations came to the aid of radio telescopes. Then followed orbital space laboratories with crews. These made it possible to employ additional types of information, such as *X*-ray and gamma radiation, as well as ultraviolet and infrared rays, which are largely absorbed by the Earth's atmosphere.

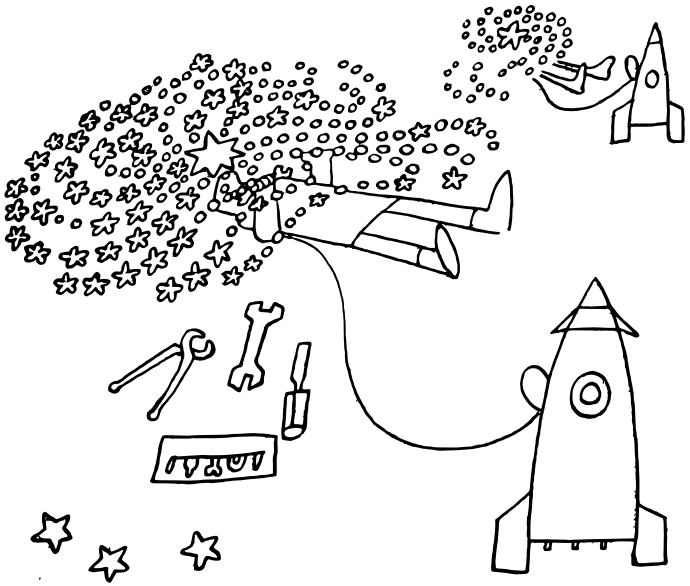
The second revolution in astronomy continues. Today its further development includes "neutrino astronomy" and the detection of gravitational waves — a new type of information from which specialists expect sensational results.

All the extragalactic objects listed above demanded inclusion in a general cosmogonic scheme, which itself could no longer remain unchanged, for no existing hypothesis could withstand such an avalanche of discoveries for long.

It was first necessary to clarify the reasons why these "abnormal" celestial objects differ from the already known — normal — ones, and only then could one attempt to generalise them. Above all, it was necessary to resolve the

question of radio galaxies: what are they, and what processes occur within them?

Specialists knew that in ordinary — normal — galaxies radio emission is produced mainly by fast charged particles of the interstellar gas, which are decelerated by galactic magnetic fields; a small contribution to radio emission is also made by stars. But for "peculiar" galaxies this radiation is negligible. What mechanism, then, gives rise to such a powerful "radio voice" in these unusual objects?



It is difficult to say whether such thoughts occurred to

the astronomer W. Baade when he first saw the radio galaxy Cygnus A on the photographic plate. The author is even inclined to think that they did not. Yet he apparently had little hope of obtaining additional information. After careful reflection on the image obtained, W. Baade suggested that before him was the result of a collision. Two stellar systems — each containing roughly one hundred billion stars — rushing towards one another at speeds of about three thousand kilometres per second, colliding head-on.

A dreadful scenario, quite worthy of a writer of science fiction. However, from the standpoint of scientific objectivity, the event would not appear so terrifying. Most likely, the stars of the colliding galaxies, like a swarm of mosquitoes, would pass calmly through one another, perhaps only slightly disturbing the individual motions of some luminaries. The distances between celestial bodies in systems such as galaxies are too vast for stars to shatter into fragments as a result of such an encounter.

W. Baade understood this better than anyone. Yet he also knew that galaxies are surrounded by extended coronas of interstellar gas. The encounter of gaseous clouds would proceed in an entirely different manner. Above all, the collision of gas clouds would be partially elastic. That is, upon meeting, the clouds would slow down, undergo compression, then rebound elastically from one another and move apart. It is here that the source of radio-emission energy might lie.

It is well known from school physics that while charged

particles move uniformly through free space, they do not reveal their presence. But once they enter a magnetic field, their trajectories begin to curve; rectilinear motion becomes curvilinear, and uniform motion becomes accelerated or decelerated. Whenever a charge undergoes acceleration, it emits electromagnetic radiation.

In the coronas of interstellar gas there are, as they say, plenty of charged particles. Among them are many so-called relativistic particles, that is, those which move at speeds comparable with the speed of light. And it is precisely the deceleration of these relativistic electrons in magnetic fields that should give rise to the very radio emission in the metre-wave range which we have learned so well to receive with the help of radio telescopes.

The collision hypothesis was coming together splendidly — simply splendidly. W. Baade rubbed his hands with pleasure as he told Rudolf Minkowski about it. He could not conceal his annoyance when his obstinate assistant doubted the validity of the hypothesis. It is not known how long the argument lasted. But it is known how it ended — with a wager on a bottle of whisky.

"Shall we test it together?" suggested W. Baade.

"Let us test it," agreed R. Minkowski.

With the aid of a spectrograph installed on the five-metre telescope, they obtained several spectra of the glow of the gas in the disputed galaxy. If the collision mechanism was indeed at work there and the gas clouds were being

decelerated, the gas atoms ought to have been in an excited state. And this could be revealed by the spectra.

The astronomers developed the plates, deciphered the resulting images and ... R. Minkowski had to "run to the shop". The wager was won by W. Baade. And a year later, at the *VIII International Astronomical Congress*, he presented his hypothesis already on behalf of both of them. The report was highly unexpected and unusual. However, despite a whole series of doubts, no objections followed immediately. That is understandable: if such specialists venture to advance a hypothesis publicly, it must be supported by arguments against which one should not step out empty-handed. But gradually, as is proper, the fruits of the initial doubts ripened. Above all, many were troubled by the low probability of a head-on collision between two galaxies. Even if one were to choose the densest cluster — and by that time a considerable number of radio sources had already been discovered in the sky — the distances between neighbours would still be too great for such collisions to occur sufficiently often.

W. Baade had foreseen such an objection and therefore hastened to calculate himself the probability of a collision for the cluster of galaxies to which Cygnus A belonged. However, the results he obtained were not very reliable. Nevertheless, Baade's authority was so great that after his address at the congress a considerable number of supporters of the collision hypothesis appeared. The supporters, too, developed theories and produced persuasive calculations "in favour".

An interesting objection was put forward by V. Ambartsumian. He said that if the authors of the hypothesis insist that at least three double galaxies emit radio waves as a result of direct head-on collisions, then they would probably agree that there must be far more oblique collisions — roughly a hundred times more. But where in the sky are there three hundred pairs of galaxies colliding with one another off-centre?

Other objections soon followed. Having calculated the amount of energy emitted by Cygnus A and the time that had elapsed since the beginning of the "collision", astronomers concluded that, in order to account for the observed radiation flux, too large a fraction of the braking energy would have to be transferred to charged particles. The efficiency, according to J. Burbidge's calculations, approached one hundred per cent. The debit clearly did not match the credit. And that is a sure sign of impending bankruptcy.

In general, the dispute over the nature of radio galaxies and the mechanism of their emission flared up throughout the world. But no discussion can be considered fruitful if it consists solely of negative remarks. Such a dispute leads into a dead end. The supporters of the viewpoint of W. Baade and R. Minkowski quite rightly asked:

— Very well, if not a collision, then what?

A positive hypothesis was needed, one that would ensure further progress in the study of the question.

And in 1956, at a conference on problems of cosmogony

held in Moscow, V. Ambartsumian "set off a bomb". No, this has nothing to do with pyrotechnics. It is merely a figurative expression to describe the effect his report produced on those assembled. He suggested that in the galaxy Cygnus A we are dealing not with the collision of two galaxies, but, on the contrary, with the splitting of one into two!

This was not an ad hoc hypothesis, as the ancient Romans used to say (the expression means "for this particular case"). The Soviet astronomer proposed a new interpretation of the observed phenomenon, basing it on his own 1954 idea of the cosmogonic activity of galactic nuclei.

According to V. Ambartsumian, the results of this activity could include the ejection of radio-emitting clouds from galactic nuclei and even the formation of spiral arms (the reader will perhaps recall that unresolved debate).

The new hypothesis contained not only much that was unexpected but also much that was unexplained. Consider, for example, the ejection of masses of gas from galactic nuclei. Previously it had been assumed that the central parts of these stellar systems consisted solely of stars. Even if one allowed for the presence of gas in the nuclei, there should have been far too little of it. From where, then, do the enormous masses of matter flowing out of galactic nuclei and producing powerful radio emission arise? Much here remained unclear.

Astronomers, for instance, knew that in the central region of our Galaxy the density of gaseous matter is no higher than at the periphery. Yet Dutch astronomers led by

J. Oort discovered that it is precisely from there, from the centre, that a continuous outflow of neutral hydrogen occurs. And the American astronomer G. M"unch detected a very similar continuous outflow of gas from the nucleus of the Andromeda galaxy. The intensity of the outflow proved to be such that within only a few million years the nucleus would eject from its depths a mass sufficient to form a good million stars like our Sun. In this hypothesis galactic nuclei appeared as bottles containing a spirit...

The contradictions seemed insurmountable. What way out did V. Ambartsumian find? At the *Sixth Moscow Conference on Cosmogony* in 1959 he declared: "We come to the conclusion that in the centres of galaxies, in their nuclei, there exist bodies many orders of magnitude more massive than ordinary stars and which are neither diffuse nebulae nor stars. This conclusion about the presence in the centres of certain galaxies of dense bodies of extraordinarily great mass seems to us an inevitable consequence of the observational data."

Thus we encounter once again the familiar idea of the Byurakan school concerning the superdense pre-stellar state of matter, only now raised to the galactic level. V. Ambartsumian maintained that after being ejected from the nuclei, the matter undergoes a series of transformations and turns into a conglomerate of stars, interstellar gas, and clouds of high-energy charged particles.

Everything seemed to proceed well. And yet one significant shortcoming diminished the value of the proposed

hypothesis: no one had ever observed matter in such a state, nor was there a theory demonstrating the possibility of the existence of such an "unusually great mass" of matter. For what was meant was a mass many, very many times greater than that of the Sun...

Unexpectedly, Ambartsumian's new concept was supported by B. Vorontsov-Velyaminov. He suggested that both Zwicky's compact galaxies and the "interacting galaxies" discovered by himself should be regarded as dispersing fragments that had once formed a single nucleus.

For the majority of astronomers, however, Ambartsumian's hypothesis was too revolutionary. Only a few from time to time ventured to speak publicly in support of the new concept.

However, while Ambartsumian's hypothesis was encountering serious difficulties, the idea of V. Baade and R. Minkowski was also "breathing its last". More and more shortcomings were being revealed in it. And when T. Matthews and M. Schmidt observed that even solitary galaxies possessed optical spectra analogous to the "colliding" components of Cygnus A, the collision hypothesis finally collapsed, burying beneath its ruins the bottle of whisky for which R. Minkowski had run in vain ten years earlier. Unfortunately, his chief, V. Baade, passed away in 1960 without ever learning that in the dispute of 1951 it was not he but his assistant who had been right. Perhaps, however, it is better to die without parting from one's illusions...

Soon after the final downfall of the collision hypothesis,

Ambartsumian's general concept of the activity of galactic nuclei received substantial confirmation. Observers detected a powerful explosion in the nucleus of the galaxy M-82. Indeed, many of the discoveries of the 1960s seemed, as if by prior agreement, to "pour water on Ambartsumian's mill".

It is interesting to recall once more the sequence of views of this outstanding Soviet astronomer. In 1947 he first advanced the assumption of the existence of superdense "D-bodies". This was followed by the idea of the activity of galactic nuclei...

The scientist had to endure much criticism and even outright rejection before his ideas began, if not to be fully confirmed, then at least to acquire a real foundation. There were the discoveries of new types of galaxies, explosions in their nuclei, and finally quasars... Are they not relatives of the mysterious "*D*-bodies"? Of course, this cannot be asserted categorically. Even today, in 1975, the assault on the quasars is still continuing. In general, the nature of superdense bodies remains unclear, although neutron stars, thanks to the discovery of pulsars, have entered the astronomical arsenal quite firmly.

Several years ago, reflecting on the causes of the expansion of stellar associations discovered by V. Ambartsumian's group, the English astronomer T. Gold posed the question: what mechanism could scatter stars in different directions? Most likely it must be an immensely powerful explosion – a super-explosion. But what could trigger it?

Perhaps there exist forces in space that compress gigantic masses of gas to the point of collapse. Then, at some stage of this unstoppable contraction, within the depths of such a clump of matter – whose mass exceeds that of the Sun many times over – sustained nuclear reactions would begin. The compression would halt. And then the collapse would turn into an anti-collapse – into a colossal explosion.

The reader has probably already noticed that the line of reasoning of the English astronomer closely resembles reflections on the hypothetical transformation of black holes" into white holes". Yet one should not forget that Gold's statements date from a time when, apart from Ambartsumian's school, relatively few theorists in the world were concerned with this problem. It was not as it is now.

Speaking at the Solvay Conference, T. Gold further developed his hypothesis. Let us suppose," he said, that such explosions may occur on an even larger scale. Then we would be approaching the concept of our colleague V. Ambartsumian..."

The idea was alluring, and some theoretical astronomers immediately set about calculating possible models. Throughout the 1960s events seemed repeatedly to work in favour of V. Ambartsumian. Arp's "blue galaxies", Zwicky's "compact galaxies", Sandage's "galaxies and quasars" – all could be fitted within the framework of his hypothesis. The explosions in galactic nuclei were, as it were, a gift to the young research group.

In time the Byurakan astronomers came to the conclusion that galactic nuclei may, apparently, explode more than once, although their activity should gradually decline. It then becomes quite plausible that among the countless stellar archipelagos one may encounter galaxies that have lost the capacity for eruptivity, as specialists like to say – that is, the capacity for outbursts – and also mature galaxies in which these processes proceed in full force. There should also be some in whose nuclei cosmogonic activity has not yet manifested itself.

It is curious that on the very day when the author was writing these lines, the postman brought a newspaper containing an intriguing note. A correspondent from Alma-Ata reported that at the high-altitude observatory of the Astrophysical Institute of the Academy of Sciences of the Kazakh SSR, a postgraduate student, L. Kondratyev, had discovered in the constellation of Serpens a highly unusual nebula composed of matter in an extremely early stage of development, about which science as yet knows very little. An interesting report. On whose scales will it add weight? To the balance of supporters of the classical view of galaxy formation from diffuse matter, or will the champions of the new hypothesis enter it on their side of the ledger?

Theoreticians today have fallen rather far behind in their attempts to comprehend and explain the facts presented by observation. It is widely understood that in the nuclei of galaxies, under conditions still entirely unknown to us, phenomena may be discovered that "could lead to a contradiction with the law of conservation of energy (and

matter) in its present form, limited to the forms of energy known to us, and require a generalisation of this law". Thus wrote V. Ambartsumian in 1962. Similar views were expressed by another Soviet astronomer — the Leningrad professor N. Kozyrev.

New sources of stellar energy? Not contraction, not nuclear burning? Then what?...

Years pass. The labour of a scientist is difficult to measure in quantitative terms. For non-specialists, for consumers of scientific results, what matters is the outcome. And what, in fact, is the result of the widely proclaimed possibilities said to be hidden within galactic nuclei? It is still too early to speak concretely. Just as the Armenian astrophysicists have not yet succeeded in constructing a theory of super-dense, massive bodies that would fully satisfy the requirements of the new line of thought, so too the theoretical development of possible new energy sources for extragalactic objects, undertaken by N. Kozyrev, has not yet gained universal recognition.

In recent years the ranks of astrophysicists have been increasingly replenished by "pure" physicists who have devoted many years of their lives to their science. Perhaps this is only natural. The walls of terrestrial laboratories are becoming too confining for modern physics.

The "Time Machine" Of The Universe

"As a result of studying the structure of cosmic bodies, I arrived at the conclusion that in nature there exist special, previously unknown forces. The source of these forces is the 'flow of time'." In roughly these words began the report of the well-known Leningrad astrophysicist N. Kozyrev, delivered in 1959 at the Geographical Society of the USSR.

His words produced jubilation among specialists of one persuasion and aroused vehement indignation among others. The theory presented by the scientist — which he called "causal, or asymmetric mechanics" — seemed far too unusual. It was described as speculative, the experiments as flawed, and the conclusions as hasty and erroneous. Yet at the same time many acknowledged the depth of the author's scientific insight into the essence of the problem, his ability to devise a subtle experiment and to draw from it consistent conclusions.

In short, Professor N. Kozyrev's proposal left no one indifferent. This is perhaps understandable, for his conclusions concerned the most commonplace, the most elusive, and seemingly the most trivial concept — time. Many of the new theory's conclusions bore directly upon cosmology. Therefore, without claiming a profound analysis, we must acquaint ourselves in this book with its principal features.

First of all, let us recall several well-known propositions — those that form the foundation of our materialist worldview and allow us to construct a picture of the world

corresponding to the present stage of society's development.

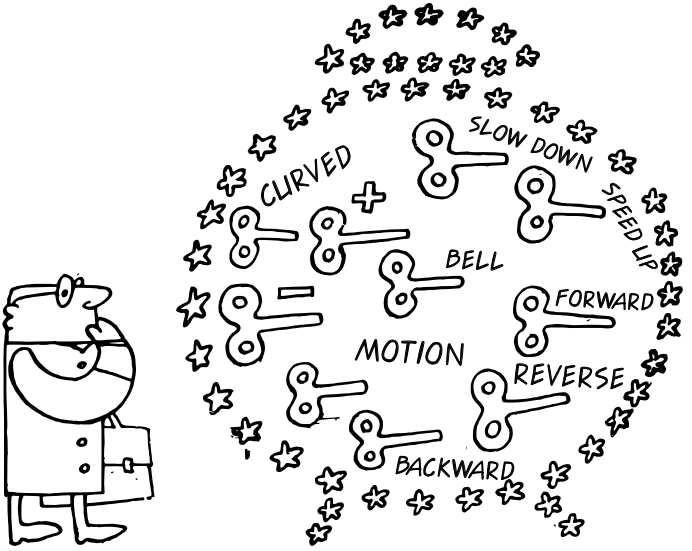
"Time is one of the fundamental (alongside space) forms of the existence of matter... Time exists objectively and is inseparably connected with moving matter... Time is inseparably linked with space, which has three dimensions, while time has one: the motion of matter in time proceeds only in one direction — from the past to the future. Time is irreversible. It is infinite."

In these postulates are contained nearly all the knowledge about time that common sense has accumulated over the years of humanity's existence.

Of the properties of time, people have known and used its duration and its one-directionality. Duration has formed the basis of all quantitative relations, measurements, and physical laws. The direction of time has determined the principle of causality, which philosophers describe as "the proposition concerning the objectivity, universality, and necessity of the causal connection of phenomena". This is the qualitative aspect of time.

From ancient times philosophers attempted to connect time with motion in order to penetrate more deeply into the nature of the former. This connection was already noted by Aristotle in his Physics. However, in antiquity, and even in the Middle Ages, the flow of time was most often correlated only with the visible motion of the celestial sphere. Philosophers of that era understood motion as ordinary mechanical displacement, and clarifying the

character of this connection often became a stumbling block for entire philosophical systems.



Natural scientists, physicists, and mathematicians were also greatly interested in the relationship between the flow of time and motion. Thus N. Lobachevsky, in his lectures on mechanics, said: "Motion that continues uniformly without end is called uniform motion, and one such motion is taken for comparison with another, and it is called time."

The theory of relativity showed that time is not merely measured by motion, but by its very nature is connected with it and, depending on motion, may alter its rate of flow.

Let us recall that from a dialectical point of view motion is understood not as simple displacement, but as any change, transformation, and development of matter.

Time is one-directional. In A. Eddington's expression, it is characterised by the "arrow of time". In this connection, journeys into the past are possible only in works of fantasy. A. Einstein, already in the 1920s, said:

> "Time, denoted in physical formulae by the letter *t*, may, of course, enter into equations with a negative sign; this makes it possible to calculate time in the reverse direction. But here we are dealing precisely with a calculation alone, from which one cannot in any way conclude that the actual flow of time can become negative. The root of the whole misunderstanding lies in confusing what is permissible and even necessary as a computational device with what is possible in reality."

It seems that everything is perfectly clear. And yet neither in physics nor in mechanics is there a single law which, taking into account the direction of time, would become absurd if the sign of the letter *t* were reversed. Does it follow that, according to these laws, the future is indistinguishable from the past?

But if that were so, then from the world we study there would vanish almost its principal property — universal objective regularity and causal determination; determinism itself would disappear. And a world in which cause-and-effect relations are broken is unknowable. It would be impossible to live in such a world. Just imagine such a

"universal anarchy". The Sun rises and sets whenever it pleases, and in the middle of July nature might amuse itself with a snowstorm and frost ... No, the world studied by science is strictly deterministic.

What, then, is to be done with the physical laws? Called upon to reflect objective reality, they nevertheless ignore the principal property of the universe — causality.

There is only one way out — to introduce the principle of causality and the direction of time into the laws of physics and mechanics.

Here it is appropriate to recall that the idea of reducing temporal order to causal order was first advanced by G. Leibniz. The German mathematician and philosopher held that space and time are merely forms of dynamic relations between things and possess no independent significance. Time, according to G. Leibniz, is the order of succession of phenomena. But where is the proof that this succession can proceed only in one direction? In the laws of physics, which reflect the essence of natural phenomena, such proof is absent.

For many years now specialists in different fields have been trying to discover in nature definite irreversible processes, in order to take them as corresponding concepts — correlates of the irreversibility of the course of time. In other words, scientists are searching for such a law of nature as would clearly reveal the one-sided direction of time in the universe.

In the nineteenth century the physicist L. Boltzmann associated the direction of time with the change of entropy. At that time entropy was called the "shadow of the queen of the world", while energy was endowed with the royal title. The interaction of energy with entropy was depicted in rather sombre colours.

"Over all that takes place in boundless space, in the stream of fleeting time, energy reigns like a goddess, like a queen — here giving, there taking away, yet on the whole neither giving nor taking. She rules with strict justice, incessantly illuminating with her calm, eternally even light both a blade of grass and a man of genius.

But where there is light, there is also a shadow cast by the sovereign of the world — energy, deep and dark, manifold and restless ... Gazing at this shadow, one cannot suppress a vague fear:

> "it is an evil demon striving to diminish, if not entirely destroy, all that is great, beautiful and good created by the bright demon. To this evil demon we give the name entropy; as it turns out, it constantly grows — and slowly but surely reveals its sinister inclinations ... Energy remains constant, entropy increases. The Sun shines, yet the shadows grow ever longer. Everywhere there is dissipation, levelling, depreciation ..."

And then, quite naturally, the author of the cited essay, written in the style of bygone times, turns to a funeral narrative about the "heat death of the universe".

Today the nightmares of the past are regarded in a more

businesslike manner. Entropy? Very well. Here is its definition: it is a state function characterising the direction of spontaneous processes in a "closed thermodynamic system". That is all. Yes, one further addition: the existence of entropy is postulated by the second law of thermodynamics.

But what of the "heat death"? After all, the first formulation of the second law of thermodynamics, due to R. Clausius, stated that a process is impossible in which heat would pass spontaneously from colder bodies to hotter ones ... R. Clausius wrote:

> "... in all natural phenomena the total amount of entropy can only increase and never decrease, and therefore we obtain, as a concise expression of the transformation process that is always and everywhere taking place, the following proposition: the entropy of the universe tends towards a certain maximum."

Later there was another formulation by W. Thomson. There were disputes as to which was better. But in the end, in modern thermodynamics too, the second law is formulated — though without drama — as a law of the increase of entropy. The final destruction of galaxies, and of the universe in general, has been declared untenable, because, first, no one yet knows what precisely occurs in the depths of galaxies or along what path they develop; secondly, there are no grounds for considering the universe a closed and isolated system; and, thirdly, it cannot be excluded that somewhere processes take place which proceed in a direction directly opposite to that required by the second

law of thermodynamics and by the common sense of the inhabitants of planet Earth.

When discussing the question of the relation between entropy and time, one should not forget that the second law of thermodynamics is a statistical law. It can be applied to a large collection of objects. But what of time? It exists for each individual object. Moreover, the theory of relativity tells us that a frame of reference — including that of time — may be associated with any single object, even a particle accelerated in a synchrophasotron. Thus, to rigidly link time with entropy is, perhaps, a dangerous undertaking. Might it not be possible to seek other correlates?

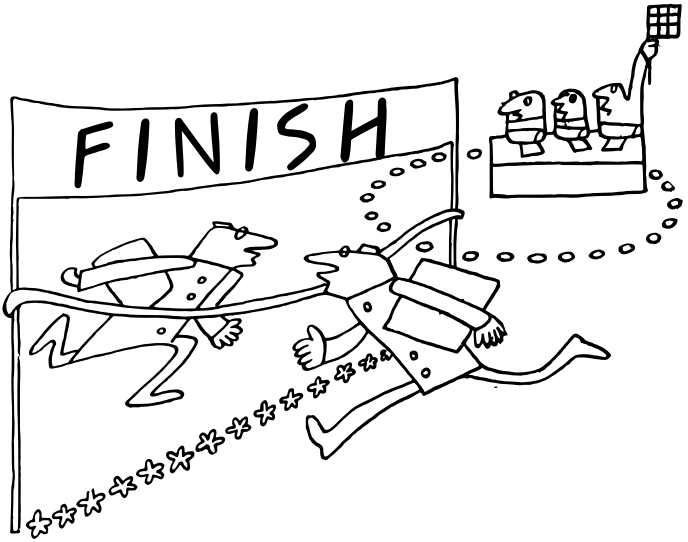
The English physicists O. Penrose and J. Percival attempt nevertheless to introduce a direction of time into the laws of physics on the basis of probability theory. Yet in their work too time turns out to be a purely statistical, averaged concept, suitable for an ensemble of objects. It is difficult to agree with this.

Finally, the American astronomer T. Gold maintains that "the expansion of the universe is responsible for the direction of time". He writes: "The pattern of the world lines of galaxies clearly shows the direction of time; it is precisely the direction in which the world lines diverge."

However, besides the expanding model of the universe, there now exist others, including pulsating models, in which at some stage expansion must give way to contraction. Does this mean that in such models time must run backwards? Thus we return once again to the problem: what is

time?

There are many statements on this subject, many points of view. The interested reader will have to decide for himself to which category the conceptions of time of Professor N. Kozyrev should be assigned — the very conceptions for the sake of which we have embarked upon the foregoing recollections.



First of all, what does the creator of the new theory mean by the term the flow of time"? After the rather prolonged introduction, this becomes easy to understand. For N. Kozyrev, the flow of time" is the rate at which physical processes occur. Which processes? Any processes at all.

In other words, it is the rate at which a cause turns into an effect. For different processes this quantity is, naturally, different, but it is limited by the speed of light in a vacuum. This is also understandable, since no material system should move faster. Thus the new quantity acquires not only physical definiteness, but also a dimension and a limiting value. Let us try to clarify it further.

It is well known that in physics some quantities possess only magnitude and are therefore called scalars. These include, for example, length and area, as well as the duration of a time interval — a second, an hour, a century. To the same category one may assign mass, density, temperature, and many other quantities that characterise matter, its state, and its motion.

Other quantities, besides magnitude, are also characterised by direction. These are called vectors. Examples include velocity, acceleration, force ...

The "flow of time", according to N. Kozyrev, turns out to be neither one nor the other; it belongs to pseudovectors. What does that mean? Consider this: if in the morning you rush towards a bus stop — your velocity is a vector. It determines the direction of motion. Now imagine yourself a champion figure skater. The final figure of your, of course, brilliant performance is a spinning top-like rotation. What is your velocity now? Now it is a pseudovector. Angular velocity, torque, and angular momentum are typical pseudovectors. To this same category N. Kozyrev assigns the flow of time". Moreover, since the direction of time is al-

ways the same, our pseudovector, as mathematicians say, has "zero rank", that is, it becomes a pseudoscalar.

We know that time is connected with space, as one form of the existence of matter is connected with another. Apparently, their properties must in some way determine one another.

An important property of space is its isotropy — that is, the independence of its properties from direction. The symmetry of our world is connected with this. However, a detailed study of the properties of atoms and molecules, crystals, and even living organisms convinces us that some fundamental absolute difference between left and right must exist in nature. What this is connected with remains unknown. After all, the concepts themselves — left and right — are conventional. In all of physics, one cannot yet find any indication of an intrinsic difference between left and right.

A similar asymmetry, apparently, must also exist between past and future. Cause and effect, when the "arrow of time" is reversed, should not yield absolute identity. And this asymmetry of time, in N. Kozyrev's view, may prove to be a powerful source of energy.

A "staggering" conclusion! But how can it be confirmed? And here we approach the most interesting point.

It is well known that rotation is a form of motion inherent in all celestial bodies. In this case, the linear velocity of any point on the surface of a rotating body has the same

dimension as the "flow of time". And what if they are added together?

It would follow that for a body rotating in one direction, the linear velocities of its points must be added to the flow of time". For bodies rotating in the opposite direction, those same velocities must be subtracted from the flow of time". Moreover, at different parallels of rotating galaxies, stars, and planets, the sum of the flow of time and the linear velocities will differ. And this difference will immediately produce a difference in momentum. Consequently, additional forces must arise. Let them be paired; let them act in opposite directions — they are still forces. Without shifting the centre of gravity of the rotating system, they may alter the total energy of the body ...

However, only experiment — only the result of experiment — can convince us of the validity of what has been said. And N. Kozyrev carried out a series of weighings of a gyroscopic top rotating in different directions. If the conclusions of his theory were correct, then in one case the gyroscope should be lighter, in the other heavier ...

Of course, a top and a pair of scales are not merely crude, primitive instruments with which one might hope to catch traces of the most elusive property of nature — time. And it must be acknowledged that the researchers understood this and did not rush to publish their conclusions. The results were not particularly reliable. Yet the more entries accumulated in the laboratory notebook, the more clearly patterns began to emerge. In the end, N.

Kozyrev and his collaborators concluded that the effect of "slimming and fattening" does exist. A 90-gram gyroscope showed a weight difference of approximately ±4 milligrams.

This result made it possible not only to calculate the absolute magnitude of the flow of time" (which N. Kozyrev denoted by C_2), found to be about 700 km/h, but also to determine its direction. Thus, for our world the flow of time" turned out to be positive in a left-handed coordinate system — the very one to which we have been accustomed since school — and negative in a right-handed system, its mirror reflection. This made it possible, for the first time, to define objectively the concepts of left and right in space through time.

Experiments with gyroscopes yielded extremely interesting results. It seemed that it was now possible to attempt to determine the force of the cause itself — that is, to distinguish the active force of physical laws from passive reaction. To do this, it was only necessary to find out which of them increases for a given direction of rotation and which decreases. In addition, the change in the "flow of time" manifested itself in the appearance of additional forces acting along the axis of rotation in opposite directions. Such forces had not previously been known in theoretical mechanics. Yet their influence is of considerable importance.

Let us imagine, in place of the spinning top, a planet — say, the Earth. In its middle region, the resultant of the addi-

tional forces is directed along the axis of rotation towards the north. But since these forces have no right to displace the planet's centre of gravity, one must assume the existence of balancing forces near the poles, directed towards the south. Consequently, the northern hemisphere, being in the grip of compressive forces, would contract, whereas in the southern hemisphere the same forces would produce stretching.

Planets are not perfectly spherical bodies. We have known this for quite some time. Previously, however, it was assumed that the Earth is compressed at the poles more or less symmetrically. Therefore, when an analysis of the motion of artificial satellites revealed that gravity is stronger in the north than in the south, specialists were somewhat perplexed. There even appeared a hypothesis about a mysterious difference in the density of matter between the two hemispheres of the Earth.

Taking into account the forces of "asymmetric mechanics", according to N. Kozyrev, deforms the Earth. Instead of a rotational ellipsoid, it acquires the shape of a rotating cardioid — a heart. The difference in the polar gravitational forces thus receives its "natural" explanation. The North Pole is simply about 200 metres closer to the centre of the Earth than the South Pole.

This asymmetry is especially evident in the cases of Jupiter and Saturn — giants composed mainly of condensed gas. Owing to their high rotational speed, the described effect should be expressed much more strongly in both

planets than on Earth. Photographs of the planetary figures confirmed the theoretical assumptions and calculations. For Jupiter, the difference in the positions of the poles relative to the centre amounted to about 400 kilometres.

With the help of the newly discovered forces, N. Kozyrev also explains certain geographical features of our planet. For example, it is known that the northern hemisphere of the Earth is considerably richer in land. This could be the result of the continents being pressed out by the new forces. The "flow of time", in the view of the creator of causal mechanics", also influences the differences in the directions of ocean currents in the two hemispheres, and the fact that the northern half of the Earth is warmer than the southern ...

Experiments with gyroscopes and balances produced yet another curious result. It appeared that the additional forces could be applied to different points of a single system. That means a couple of forces arises. And time, to which they owe their origin, must then possess not only energy but also angular momentum. For the moment, it merely turns the beam of the balance. From the point of view of cosmogonic hypotheses, it is important that this moment can be transmitted to a system.

Of course, the properties of time are difficult to visualise clearly if one relies only on familiar analogies. There are too many fundamental differences. But if one accepts the proposed interpretation of the experimental results, one may arrive at yet another conclusion: because of pro-

cesses occurring in nature, or as a result of deliberate human action, the density of time may change. And then the question arises: is it not possible, through time, for one material system to act upon another? For this, one need only assume that causal changes occur not only in time, but also by means of time. Or that in any natural process time is either expended or ... produced ...

As we have established, the "flow of time" has a finite speed. However, time itself is not transmitted through the universe with any finite velocity. Time arose at once, simultaneously with the birth of the world, and in all its corners at the same moment. Perhaps this circumstance will one day make it possible, by altering the properties of seconds, to transmit information instantaneously across the entire universe, regardless of distance?

N. Kozyrev's hypothetical theory conceals much that is unexpected and controversial. In his "causal mechanics" there are many interesting insights, such as the hypothesis of the discontinuity of time or of the "atoms of time". Their development belongs to the future.

For the present, N. Kozyrev's views are far from being universally accepted, and it is difficult today to assess the degree of truth in the opinions expressed both by supporters and by opponents of the new theory. Yet the hypotheses underlying it impress and attract by their boldness even those who are accustomed to the most revolutionary turns in the science of our century.[16]

Time is perhaps the most inaccessible summit upon

[16] Nikolai Kozyrev's "causal mechanics", including the idea that time generates asymmetric forces deforming planets into cardioid shapes, has not been confirmed and is not accepted in modern physics. Precise satellite geodesy shows that Earth is an oblate spheroid with small irregularities due to rotation and internal mass distribution, while the shapes of Jupiter and Saturn are accurately explained by hydrostatic equilibrium under classical gravity. No additional "asymmetric" forces are required. – DM

which our understanding of the system of the world and our interpretation of its picture rest. The exact sciences have so far tried to avoid this summit, making as though it did not even exist. But it seems that its time has come as well. Well then, a happy ascent, as mountaineers say.

So how, after all, are galaxies born?

Hubble's original classification of galaxies has become outdated, especially after the appearance of W. Baade's famous work on stellar populations. As new data on galaxies accumulated, E. Hubble himself repeatedly attempted to revise and supplement his classification. However, his work was interrupted by his death.

In 1957, the astronomers W. Morgan and M. Mayall proposed a new classification. It was based on the criterion of increasing central brightness concentration, already indicated by E. Hubble, but the direction of evolution in their scheme turned out to be the reverse of Hubble's. They divided the whole diversity of extragalactic objects into seven classes. The first included irregular galaxies without a visible nucleus. Then, as the brightness of the nucleus increased, came the second, third, fourth, fifth, and sixth classes, which also included spiral galaxies.

At the same time, with increasing class, the degree of winding of the spiral arms decreased. The seventh class brought together various types of elliptical galaxies. A definite advance of the new classification was that, whereas

previously a galaxy's spectral class had been assigned on the basis of the total radiation of all the stars it contained, Morgan and Mayall now attempted to answer the question: which types of stars make the greatest contribution to the integrated radiation?

Naturally, having devoted so much time and effort to the study of galactic nuclear activity, V. Ambartsumian was bound to propose his own classification. And he did so, dividing the existing objects into five classes according to their degree of cosmic activity. The first class included galaxies without a noticeable nucleus and even without a noticeable central concentration. These include many irregular galaxies, among them probably our neighbour — the Magellanic Clouds — as well as dwarf elliptical galaxies, such as the one discovered in the constellation Sculptor.

In the second class he grouped galaxies with a calm, not very bright nucleus. These include our Galaxy, the Andromeda Galaxy — M 31 — and the galaxies M 33 and NGC 5194.

Let us recall that the letter M in a galaxy's designation indicates that it belongs to the Messier catalogue, while "NGC" stands for the New General Catalogue compiled by J. Dreyer. One may also encounter galaxies whose serial number is preceded by the letter "C". This means that they are to be found in the supplement to the New General Catalogue.

The third class comprises galaxies that also have calm but significantly brighter nuclei, for example NGC 4303

and NGC 3162.

The fourth class includes galaxies similar to Seyfert galaxies. They possess not merely bright but excited nuclei.

Finally, the fifth class consists of those stellar systems in which almost all the brightness is concentrated in the nucleus. These include Zwicky's "compact" galaxies, certain "blue galaxies", and quasars.

Astronomers from Armenia believe that it is precisely the study of galactic nuclei that promises the greatest progress in resolving such fundamental questions as the origin and evolution of these stellar systems.

In 1964 V. Ambartsumian stated that he regarded evolution as proceeding from the stage of an elliptical galaxy with a young nucleus and a rich stellar population of Baade's Population II. As such a galaxy develops, the luminosity of its nucleus should increase; gradually new subsystems begin to form within it; from matter ejected into space by the nucleus, spiral arms are created; and the galaxy passes into the stage of spiral systems (or barred spirals). At this stage, Baade's Population I is formed in them. Gradually, the bright nuclei of spiral galaxies then fade, and the systems pass into a new phase of irregular galaxies.

Ambartsumian's colleague L. Mirzoyan admits that "at present the hypothesis of the origin of galaxies as a result of the activity of dense, massive nuclei cannot yet, of course, explain all the physical and dynamical properties of galaxies. For example, in the formation of galaxies from bodies of small volume it is still difficult to explain the enor-

mous angular momenta observed in a number of galaxies. This hypothesis also encounters other, less serious difficulties." Nevertheless, L. Mirzoyan remains optimistic. He fully shares V. Ambartsumian's conviction that

> "the study of explosions and other manifestations of non-stationarity in galaxies leads us towards solving the problems of the origin and evolution of galaxies, as well as the problem of the transformation of non-stellar bodies located in galactic nuclei into ordinary stars and nebulae."[17]

In 1967 the English astronomer M. Ryle, comparing the spectra of quasars and radio galaxies, suggested that both are simply different stages in the evolution of the same objects. After all, both represent double systems, differing only in the distances between their components. At the same time, the radio emission power of close pairs is clearly greater. Ryle's hypothesis was that a radio source begins its life as a very close pair, or perhaps even as a single object of high activity. Gradually, over roughly one hundred thousand years, the plasma clouds ejected by the nucleus, which account for a significant share of the observed radio emission, move away and disperse. Naturally, in the process the object's "radio brightness" decreases substantially.

In 1970 the Soviet astronomer L. Ozernoy, proceeding from the idea that any galaxy in the course of normal development may suddenly pass into an excited state, constructed an interesting diagram. On it, the horizontal axis represents the sequence of normal galactic development

[17] Ambartsumian's proposed sequence — elliptical galaxies evolving into spirals through nuclear ejection of matter — is not supported by modern evidence. Observations since the 1970s show that most elliptical galaxies are gas-poor systems typically formed through mergers, while spiral galaxies require long-lived, rotating gas discs. There is no established evolutionary path from elliptical to spiral. However, Ambartsumian's emphasis on nuclear activity anticipated the later recognition (from the 1960s onward) that many galaxies host active nuclei powered by supermassive black holes, which can influence star formation through feedback, though not in the manner he envisaged. – DM

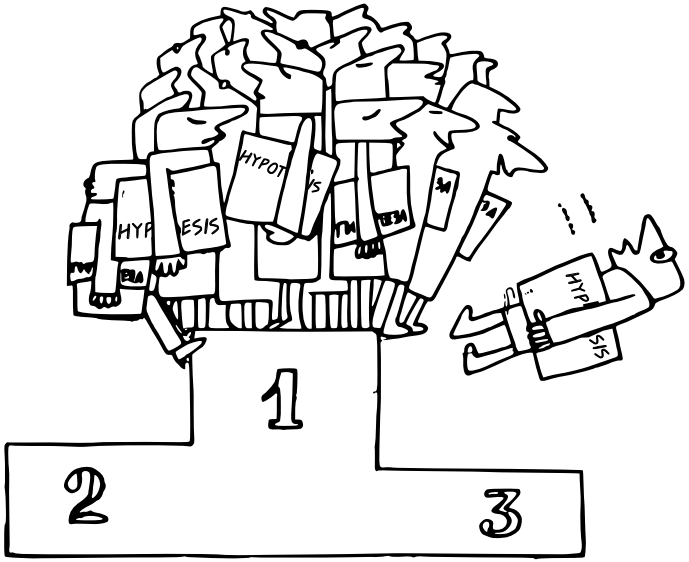
(from irregular to spiral, then to elliptical, and so forth), while the vertical axis shows the possible transitions into an excited state from each form. In this scheme, elliptical galaxies in an excited state become powerful radio galaxies, while spiral galaxies become Seyfert galaxies. This transition occurs through intermediate stages, which may be "compact" galaxies.

"N-galaxies" and quasars are objects already in an extremely excited state. Ozernoy regarded the stages of Zwicky's "compact" galaxies and quasars as intermediate positions for them. However, their original forms remain unknown. In the new diagram a place was found for all the varieties of galaxies known today. But what will await it tomorrow?

In the same year, two other Soviet specialists V. Komberg and R. Sunyaev proposed a different scheme for the development of galaxies. In their view, at the very earliest stage of formation, quasi-stellar objects first arise from large clusters of diffuse matter: quasars, quasagi, or perhaps some other quagi". In such a childishly excited state, celestial objects exist for a comparatively short time — no more than a million, or at most ten million, years. Then youth begins — an intermediate state.

The unknown "quagi" turn into the nuclei of Seyfert galaxies, quasars transform into Zwicky's "compact" galaxies, and quasagi become the nuclei of "N-galaxies". The youth of galaxies lasts roughly an order of magnitude longer than their childhood. Then maturity begins. Extragalac-

tic objects enter the main stage of their existence, which lasts about 10 billion years. Seyfert galaxies become spiral galaxies, "compact" galaxies become elliptical ones, and the nuclei of "N-galaxies" turn into the nuclei of powerful radio galaxies.



Both L. Ozeroy and V. Komberg with R. Sunyaev regard the Hubble types of galaxies as the normal state of extra-galactic objects. Today it is difficult to give preference to any one of the proposed evolutionary schemes. Most likely, in the dispute between two, someone third will be right — someone who will later give way to a fourth, the fourth

to a fifth, and so on, because the process of knowledge is endless and, contrary to all the prophets of the decline of human culture, it is unlikely ever to grow seriously tiresome for us.[18]

In Service — New Technology...

Remember, when beginning our discussion of "abnormal" galaxies, we listed a whole series of new extragalactic objects. Most of them are so distant from the Earth and from the Galaxy that the information available to specialists about them is literally negligible. Meanwhile, these new objects clearly play a significant role in cosmogony. This is evident at least from the latest hypotheses. In general, to construct new schemes for the evolution of any celestial objects, one must first discern their interconnections. And that means — a maximum of information about the objects themselves is required.

Yet it is not only that they are far away. The Earth's greatest treasure, the happiness of its inhabitants — the atmosphere — is a misfortune for astronomers. Neither infra-, nor ultra-, nor *X*-, nor gamma rays penetrate through its thickness. All radiation harmful to organic life is reliably absorbed by the atmosphere. And scientists need it!

In recent years, a view has gradually crystallised among specialists that the principal range of electromagnetic waves through which most energy release occurs in the Galaxy and in the Universe is infrared radiation. Interesting? Very

[18] The scheme proposed by V. Komberg and R. Sunyaev — in which quasars and other compact objects represent an initial evolutionary stage that later develops into specific Hubble types — is not supported by modern evidence. Since the 1970s, quasars have been firmly identified as active galactic nuclei powered by accretion onto supermassive black holes within already formed galaxies. They do not evolve into spirals or ellipticals; rather, they represent a temporary phase of nuclear activity. Galaxy morphology is now understood to depend chiefly on mass, angular momentum, gas content, mergers, and environment, while active phases can occur at different times in a galaxy's history. – DM

much so. Yet it cannot be observed from the Earth's surface. What is to be done?

Furthermore, in the words of the director of the Crimean Astrophysical Observatory, Academician A. Severny, it is precisely the ultraviolet and *X*-ray radiation of our luminary that holds the key to the mysteries of its sudden flares. And the Sun is a star. Galaxies, in turn, are made up of stars. But, alas, from this intriguing range nothing can be extracted at the Earth's surface — not to mention gamma rays. Where, then, is the way out?

Thus, in January 1975, a "research institute of broad profile" began its work in near-Earth orbit. This is how the press described the activity of Soviet cosmonauts A. Gubarev and G. Grechko aboard the station *Salyut-4*.

During their month-long mission beyond the atmosphere, the cosmonauts carried out an enormous volume of work, devoting a considerable portion of their flight time to astronomical, astrophysical, and radiophysical investigations.

A cryogenic infrared telescope–spectrometer, ITS-4, was installed aboard the station. Such equipment had been placed in orbit for the first time. The cold of the cryostat, in which the radiation detector was housed, increased the sensitivity of the instruments hundreds of times, making it possible to obtain unique information. The device was intended for the study and creation of infrared "portraits" of the Earth and other planets, for the investigation of matter in interplanetary and interstellar space at the molecular

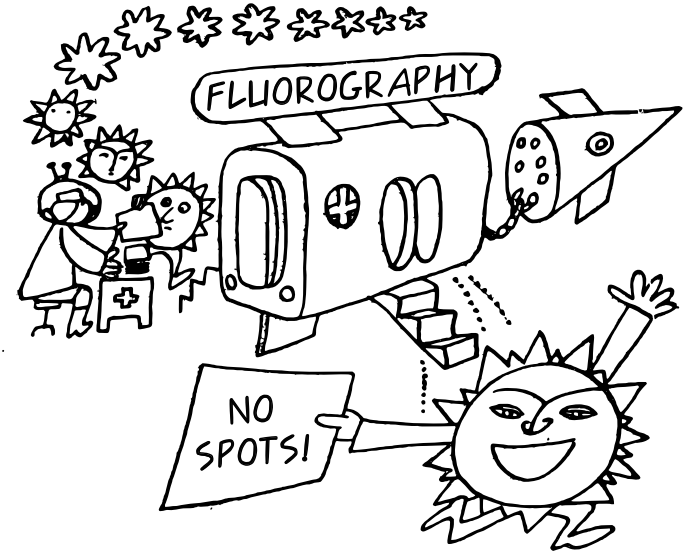
level, and for the observation of distant, non-stationary objects located in the plane of the Galaxy. It is precisely the study of these latter objects that should help in understanding the laws governing the life of the Galaxy and of galaxies.

In addition, the cosmonauts devoted much effort to observations of the Sun, using an orbital solar telescope equipped with a short-wave diffraction spectrometer for ultraviolet radiation, OST-1. Recall A. Severny's words about the key to the mysteries of solar flares.

A complex of instruments for the serious study of *X*-ray radiation was also installed aboard *Salyut*-4. Its creators named their offspring "Filin" ("Eagle Owl"). During a single orbit of the station, Filin surveyed a strip of the starry sky about 10 degrees wide, recording everything that entered its field of view. The information was immediately transmitted to Earth. Thus Salyut-4 may be said to have been the principal experimental department of a large research institute, whose ground division consisted of numerous scientific workers, keenly envying the cosmonauts and impatiently awaiting their share of information. In fairness, *Salyut-4* disappointed no one. The volume of new data transmitted by A. Gubarev and G. Grechko will suffice for several years of intensive and, one hopes, fruitful work by their colleagues on Earth.

X-ray astronomy is in general a very young branch of the ancient science of the stars. The first cosmic source of *X*-ray radiation after the Sun — Scorpius X-1 — was dis-

covered only in 1962. Since then, only a few experiments have been carried out with instruments lifted beyond the atmosphere on sounding rockets and on Soviet satellites.



In 1970, American specialists launched the first specialised satellite, *Uhuru*, intended for the observation, classification, and identification of *X*-ray sources with optical and radio objects. Although the equipment aboard this satellite was still quite imperfect, the results of its work proved to be rather good. The *Uhuru* catalogue contained extensive information on 163 sources of *X*-ray radiation, 108 of which had previously been unknown.

The information gathered by the satellite made it possible to draw an interesting conclusion: in space there exist close binary systems in which one of the components is a source of *X*-ray radiation. Two such sources — Hercules *X*-1 and Centaurus *X*-3 — are *X*-ray pulsars. If one accepts that the strict periodicity of their emission is caused, as in ordinary radio pulsars, by the rapid rotation of the object about its axis, then their dimensions must be extremely small. Consequently, the density of their matter must be enormous. This makes it possible to suppose that both of the named *X*-ray pulsars are neutron stars.

The situation is different with the *X*-ray source Cygnus *X*-1. According to calculations, its density must be even greater than that of the objects mentioned above. And this means that Cygnus *X*-1 may prove to be a "black hole".

More than forty *X*-ray sources from the latest *Uhuru* catalogue have been identified with extragalactic objects. Their study was continued by the American artificial satellites *OSO-7* and *Copernicus*, as well as by the crew of the orbital laboratory *Skylab*, launched in 1973.[19]

In 1973, on the basis of data from gamma-quantum counters installed on Earth satellites, specialists detected puzzling short bursts of low-energy gamma radiation of high intensity. It was suggested that their sources lay outside the Solar System, and possibly even beyond the limits of the Galaxy. The brief duration of the bursts also indicated that the sources themselves were probably small in size. At present, theorists consider neutron stars to be the

[19] The main conclusions drawn from the 1970 Uhuru mission were broadly confirmed. Sources such as Hercules *X*-1 and Centaurus *X*-3 are indeed accreting neutron stars in close binary systems. Cygnus *X*-1, long suspected of harbouring a black hole, is now firmly established as one of the first confirmed stellar-mass black holes, with a mass of about 20 solar masses. Modern *X*-ray astronomy has shown that such systems are powered by accretion onto

most likely candidates for the sources of gamma bursts, since, according to recently developed theories, they are capable of sudden eruptions of radioactive matter from their depths.

As always, new means devised to help explain old mysteries bring with them new ones of their own. In this, perhaps, lies one of the laws of development — the laws of progress.

Conclusion

In conclusion, the author would like to say that he has sought to present the hypotheses in such a sequence that they might convey not so much the "action" itself, in which the worlds around us are participants, as our own, human approach to understanding them.

Before the reader's eyes there has passed a multitude of ideas, hypotheses, and theories. Where, then, is the truth? — he is entitled to ask. There is no unambiguous answer. In cosmology there is no single point of view equally acceptable to representatives of different schools. Each of them will answer the question of truth in his own way. It is bad when there is no answer at all. But a multitude of different answers is no better — especially when the latest of them proves unreliable. If a clock strikes thirteen times, doubt arises not about the reality of the passage of time, but about the correctness of the clock itself...

So many wise, respected people have struggled intensely

to understand the cherished mechanism behind the origin of worlds. They drew upon the most modern, most sophisticated achievements of the human intellect. Yet time passed, and the ingenious constructions first appeared naïve, then proved to be incorrect. They were replaced by new ones — which came only to share the fate of their predecessors...

Is this bad or good? Cosmology is in a state of searching. This means that its vital potential is high. And such a science is young. There remains an untapped vastness of work ahead, magnificent difficulties, and brilliantly promising discoveries.

In present-day cosmology there is an extraordinarily wide field for the application of youthful energies. New hypotheses and new theories await us. Of course, they too will be refuted and replaced by subsequent ones. Yet each of them advances us, slowly and persistently, step by step, along the endless spiral of humanity's understanding of the world.

9 Postface – Damitr Mazanav

When this book was written in 1975, cosmology and high-energy astrophysics were relatively young, exploratory sciences. Many of the phenomena described such as the *X*-ray sources, gamma bursts, infrared emission from galaxies, neutron stars, and the possible existence of black holes, were still uncertain hypotheses supported by fragmentary data from early satellites and short-lived missions. Half a century later, the situation has changed profoundly. Yet the spirit of that earlier search remains recognisable: each new discovery has opened further questions.

One of the central themes was the importance of observing the Universe beyond the visible spectrum. At that time this required lifting instruments above the atmosphere for brief intervals. Today, space astronomy is systematic and continuous. Observatories such as Hubble, Chandra, XMM-Newton, Spitzer, Herschel, Fermi, Planck, and the James Webb Space Telescope have surveyed the sky across the electromagnetic spectrum with sensitivities unimag-

inable in the 1970s. Infrared astronomy, once technically fragile, has become one of the principal tools for studying star formation, planetary systems, and the early Universe. We now detect galaxies whose light began its journey more than 13 billion years ago, probing epochs close to the formation of the first stars.

X-ray astronomy, described in the book as a very young field, is now mature and precise. Thousands of *X*-ray sources have been catalogued and classified. The nature of many compact *X*-ray binaries is well understood: matter from a normal star accretes onto a neutron star or black hole, releasing enormous energy as it spirals inward. Pulsars are firmly identified as rotating neutron stars with intense magnetic fields, their regular pulses explained by detailed models. Cygnus X-1, once cautiously discussed as a "possible" black hole, is now established as a stellar-mass black hole. Indeed, black holes are no longer speculative theoretical constructs. Precise measurements of stellar orbits at the centre of our Galaxy reveal a supermassive black hole of about four million solar masses. Similar objects appear to inhabit the centres of most galaxies.

A symbolic milestone occurred in 2019, when the Event Horizon Telescope collaboration released the first direct image of a black hole's shadow, in the galaxy M87. By linking radio telescopes across the globe into an Earth-sized virtual instrument, astronomers resolved a dark central region surrounded by a bright ring of emission — the silhouette of the event horizon against glowing infalling gas. In 2022 a similar image of the black hole at the centre of our

own Galaxy was presented. These images did not merely illustrate a theory; they provided direct visual evidence of the space-time geometry predicted by general relativity in the strong-gravity regime.

Gamma-ray bursts, which in the 1970s were mysterious flashes of uncertain origin, are now understood in broad outline. Observations since the 1990s have shown that they are cosmological in distance. Short bursts are associated with mergers of neutron stars; long bursts with the collapse of massive stars into black holes. This interpretation was confirmed in 2017, when gravitational waves from a neutron star merger were detected simultaneously with a short gamma-ray burst. That event marked the beginning of multi-messenger astronomy: the coordinated use of electromagnetic radiation, gravitational waves, neutrinos, and cosmic rays to study single cosmic phenomena.

Gravitational wave astronomy itself represents one of the most significant developments of recent decades. In 2015 the LIGO detectors observed the merger of two black holes, directly confirming a prediction of general relativity made a century earlier. Numerous further detections have followed, involving both black holes and neutron stars. Compact objects once inferred indirectly are now studied through the ripples they produce in space-time.

Cosmology has undergone a comparable transformation. Measurements of the cosmic microwave background radiation, especially by the *Planck* satellite, have determined the age of the Universe to about 13.8 billion years

with impressive precision. Large-scale surveys have mapped the distribution of galaxies across vast cosmic volumes. Yet new puzzles have emerged. In the late 1990s it was discovered that the cosmic expansion is accelerating. This acceleration is attributed to dark energy, whose physical nature remains unknown. Moreover, most matter appears to consist of dark matter, detected only through its gravitational influence. Thus, while cosmology has become quantitatively exact, its fundamental constituents are still partly mysterious.

Infrared and submillimetre astronomy have clarified the processes of star and planet formation. Dense molecular clouds are observed in detail. Thousands of exoplanets have been discovered, revealing that planetary systems are common and varied. Some exoplanets reside in habitable zones, and their atmospheres are being examined for chemical signatures. The question of life beyond Earth, once largely speculative, has become an empirical scientific endeavour.

Our understanding of galaxy evolution has deepened through both observation and numerical simulation. Galaxies grow by mergers and gas accretion; star formation rates evolve over cosmic time. Supermassive black holes influence their host galaxies through energetic feedback processes. Powerful computers now simulate the growth of cosmic structure from initial fluctuations in the early Universe to the web-like distribution of galaxies observed today.

Yet certain classical problems remain open. The detailed mechanism of supernova explosions is still debated. The internal composition of neutron stars is uncertain. The identity of dark matter particles and nature of dark energy is unknown. Even the present expansion rate of the Universe shows a discrepancy between different measurement techniques. Progress has sharpened the questions rather than eliminated them.

Technically, astronomy has become global and collaborative. Observatories operate on multiple continents and in orbit. Data archives are widely accessible. Automated surveys monitor the sky continuously, detecting transient phenomena in real time. The scale and precision of instrumentation would have appeared extraordinary in 1975. Yet the intellectual posture remains similar: careful observation, cautious interpretation, and readiness to revise.

In retrospect, many hypotheses discussed decades ago have been confirmed in essence, though refined in detail. Neutron stars, black holes, and high-energy cosmic events are established realities. Space-based observation is indispensable. However, the expectation that each generation's theories would be superseded has also proved accurate. Dark energy, gravitational waves, and direct black hole imaging were not foreseen in their present form.

Cosmology today is both more secure and more enigmatic. Its measurements are precise; its models are mathematically rigorous; its data sets are vast. Yet most of the Universe consists of components whose physical nature

is still unclear. The spiral of knowledge continues. Each advance reveals deeper structure and wider horizons. The search has not ended; it has merely become more exacting.